THE ARCHAEOMETALLURGY OF IRON

Recent Developments in Archaeological and Scientific Research

Edited by Jiří Hošek, Henry Cleere & Ľubomír Mihok

Institute of Archaeology of the ASCR, Prague, v.v.i. | Prague 2011

Comité Pour la Sidérurgie Ancienne

THE COMMITTE FOR ANCIENT IRONWORKING

https://independent.academia.edu/CPSA

Archeologický ústav AV ČR, Praha, v.v.i.

INSTITUTE OF ARCHAEOLOGY
OF THE CAS, PRAGUE, v.v.i.

Letenská 4, 118 01 Prague 1 - Malá Strana; Czech Republic
http://www.arup.cas.cz

Pdf version of this book was created by CPSA and with consent
of the Institute of Archaeology of the Czech Academy of Science, Prague, v.v.i.,
was made available on-line for those who deal with
or who are interested in early ironworking.

This pdf file is available at:

Reference:
Hošek, J. – Cleere, H. – Mihok, Ľ. (eds.) 2011. The Archaeometallurgy of Iron.
Recent Developments in Archaeological and Scientific Research.
Prague: Institute of Archaeology of the ASCR, Prague, v.v.i.

THE ARCHAEOMETALLURGY OF IRON

Recent Developments in Archaeological and Scientific Research

Dedicated to Professor
Radomír Pleiner

Edited by
Jiří Hošek, Henry Cleere and Ľubomír Mihok

The book was printed with the support of the Academy of Science of the Czech Republic

THE ARCHAEOMETALLURGY OF IRON
Recent Developments in Archaeological and Scientific Research

Published by the Institute of Archaeology of the ASCR, Prague, v. v. i.
Letenská 4, 118 01 Praha 1, Czech Republic

Editors: Jiří Hošek, Henry Cleere and Ľubomír Mihok
Copy editor: Petr Meduna
Setting: Johana Brokešová
Cover: Jiří Hošek
Printed by Helvetica & Tempora, s. r. o.,
Pod kaštany 246/8, 160 00 Praha 6

© The Institute of Archaeology of the ASCR, Prague, v. v. i.
and the Authors, 2011

ISBN 978-80-87365-41-0

Available at: Archeologický ústav AV ČR, Praha, v. v. i.
Letenská 4, 118 01 Praha 1, Česká republika
Fax: +420 257 532 288
knihovna@arup.cas.cz

List of authors

Sylvain Bauvais
Laboratoire Métallurgies et Cultures, UMR 5060 IRAMAT CNRS, Université de Technologie de Belfort-Montbéliard. Site de Sévenans. 90010 BELFORT Cedex, France et LAPA/SIS2M UMR3299 CEA/CNRS Bat. 637, CEA Saclay, 91191 Gif Sur Yvette Cedex, France
protosly@hotmail.com

Marion Berranger
Laboratoire Métallurgies et Cultures, UMR 5060 IRAMAT CNRS, Université de Technologie de Belfort-Montbéliard. Site de Sévenans. 90010 BELFORT Cedex, France
marion.berranger@utbm.fr

Kazimierz Bielenin
ul. Altanowa 18/97, 30-132 Kraków, Poland
no e-mail

Eleanor Blakelock
University of Bradford, Department of Archaeological Science, Bradford, West Yorkshire, BD7 1DP, UK
eleanor.blakelock@blueyonder.co.uk

Henry Cleere
Acres Rise, Ticehurst, Wadhurst TN5 7DD, UK and Institute of Archaeology, University College London
henry.cleere@btinternet.com

Peter Crew
Pen Cefn, Penrhyndeudraeth, Gwynedd LL48 6DR, UK
petercrew@deudraeth.net

Philippe Dillmann
Laboratoire Métallurgies et Cultures, UMR 5060 IRAMAT CNRS, Université de Technologie de Belfort-Montbéliard. Site de Sévenans. 90010 BELFORT Cedex, France et LAPA/SIS2M UMR3299 CEA/CNRS Bat. 637, CEA Saclay, 91191 Gif Sur Yvette Cedex, France
Philippe.dillmann@cea.fr

Arne Espelund
Institutt for materialteknologi, NTNU, 7491 Trondheim; Norway
ne.espelund@material.ntnu.no

Philippe Fluzin
Laboratoire Métallurgies et Cultures, UMR 5060 IRAMAT CNRS, Université de Technologie de Belfort-Montbéliard. Site de Sévenans. 90010 BELFORT Cedex, France
Philippe.Fluzin@utbm.fr

János Gömöri
Soproni Múzeum, 9400 Sopron, Fő tér 6, Hungary
gomori@ggki.hu

Jiří Hošek
Archeologický ústav AV ČR, Praha, v.v.i., Letenská 4, 118 01 Praha, Czech Republic
hosek@arup.cas.cz

Michael F. Charlton
Institute of Archaeology, University College London, 31–34 Gordon Square, London WC1H 0PY, UK
mike.charlton@ucl.ac.uk

Arne Jouttijärvi
Skovledet 30, DK-2830 Virum, Denmark
heimdal@archaeometry.dk

Vjatcheslav G. Kotigoroshko
Uzhgorodskij nacionalnij universitet, 88000, Trascarpathia , Uzhgorod, Pidhirna str. 46, Ukraine; Institute of Carpathian Sciences, Uzhgorod, Ukraine

Janet Lang
The British Museum, London WC1B 3DG, UK
j.r.s.lang@btinternet.com

Gerry McDonnell
Gerry McDonnell Archaeometals, Blythe House, Woonton, Hereford HR3 6QN, UK
gerry_mcdonnell@btconnect.com

Petr Meduna
Archeologický ústav AV ČR, Praha, v.v.i., Letenská 4, 118 01 Praha, Czech Republic
meduna@arup.cas.cz

Jiří Merta
Technické muzeum v Brně, Purkyňova 105, 612 00 Brno, Czech Republic
merta@technicalmuseum.cz

Ondřej Merta
Technické muzeum v Brně, Purkyňova 105, 612 00 Brno, Czech Republic
merta@technicalmuseum.cz

Ľubomír Mihok
Technická univerzita v Košiciach, Letná 9, 042 00 Košice, Slovak Republic
Lubomir.Mihok@tuke.sk

Szymon Orzechowski
Uniwersytet Humanistyczno-Przyrodniczy Jana Kochanowskiego w Kielcach, Instytut Historii, ul. Żeromskiego 5, 25-369 Kielce, Poland
simon@ujk.kielce.pl

Gaspard Pagès
Laboratoire Métallurgies et Cultures, UMR 5060 IRAMAT CNRS, Université de Technologie de Belfort-Montbéliard. Site de Sévenans. 90010 BELFORT Cedex, France et Laboratoire d'Archéologie des Sociètés Méditerranéennes, UMR 5140 CNRS, CDAR, 390 avenue de Pérols. 34970 LATTES, France
gaspard.pages@gmail.com

Ludmila S. Rozanova †
Institut archeologii RAN Moskva, Ul. Dm. Ulyanova, 19, 117036, Moscow, Russia

Chris Salter
University of Oxford, Department of Materials, Sandy Lane, Kidlington OX5 1PF, UK chris.salter@materials.ox.ac.uk

Věra Souchopová
Technické muzeum v Brně, Purkyňova 105, 612 00 Brno, Czech Republic
souchopova@technicalmuseum.cz

Karel Stránský
Vysoké učení technické v Brně, Fakulta strojního inženýrství, Technická 2896/2, 616 69 Brno, Czech Republic
stransky@fme.vutbr.cz

Natalia N. Terekhova
Institut archeologii RAN Moskva, Ul. Dm. Ulyanova, 19, 117036, Moscow, Russia
no e-mail

Edmond Truffaut
2 Chemin des Anglais, St Etienne au Mont, 62360 Pont de Brique, France
edmondtruffaut@aol.com

Olfert Voss
Grøndalsvej 47, DK-2000, Frederiksberg, Denmark
olfert.voss@gmail.com

Galina A. Voznesenskaya
Institut archeologii NAN Ukrainy, 12 Geroiw Stalingradu ul., Kyiv, Ukraine
no e-mail

Alan Williams
The Wallace Collection, Hertford House, Manchester Square, London W1U 3BN, UK
alan.williams@wallacecollection.org

Vladimir I. Zavyalov
Institut archeologii RAN Moskva, Ul. Dm. Ulyanova, 19, 117036, Moscow, Russia
v_zavyalov@list.ru

Contents

Foreword 1

Radomír Pleiner: the magister ferrariarum at 80
by H. Cleere 3

Examples of ancient bloomery furnaces and the development of iron metallurgy in Europe 29

A new perspective on the ancient slag-pit bloomery smelting furnace
by K. Bielenin 31

The canal-pit and its role in the bloomery process: the example of the Przeworsk culture furnaces in the Polish territories
by S. Orzechowski 41

The oldest iron-smelting furnaces in Denmark
by A. Jouttijärvi and O. Voss 55

Some results and questions of the archaeometallurgy in Hungary
by J. Gömöri 65

Some aspects of the development of Great Moravian iron metallurgy
by V. Souchopová, J. Merta and O. Merta 73

Norway as a bloomery iron producer
by A. Espelund 87

Examples of research on ancient and early European iron forging 99

The chemical and metallographic analyses of the prehistoric ring from the "Bull's Rock" cave
by K. Stránský 101

The craft of the Dacian blacksmiths
by Ľ. Mihok and V. G. Kotigoroshko 107

Early medieval knife manufacture in Britain; a comparison between rural and urban settlements (AD 400–1000)
by E. Blakelock and G. McDonnell 123

Metallography of knives from the medieval village of Hrdlovka and the burial ground of Zlončice, Bohemia
by J. Hošek and P. Meduna 137

Technological traditions in the craft of the blacksmith in old Russian Shestovitsa
by G.A. Voznesenskaya 153

Further metallographic studies on early armour from Churburg
by A. Williams 163

From Soissons to Beauvais: the use of iron in some French cathedrals
by P. Dillmann 173

Examples of involvement of archaeometallurgy into archaeological, historical and historical-technological research 197

Archaeological metallography in Russia: historiographic notes
by V.I. Zavyalov 199

Archaeometallography in solving historical and cultural problems
by V.I. Zavyalov, L.S. Rozanova and N.N. Terekhova 211

The multidisciplinary approach (archaeology and archaeometry) to bloomsmithing activities in France: examples of results from the last 20 years
by P. Fluzin, S. Bauvais, M. Berranger, G. Pagès and P. Dillmann . 223

Examples of experimental archaeometallurgy 197

Cast iron from a bloomery furnace
by P. Crew, M. Charlton, P. Dillmann, P. Fluzin, C. Salter and E. Truffaut 239

The Celtic sword: a source of practical inspiration
by J. Lang 263

Index of places 273

Summary in Czech (Souhrn) 277

Plates 287

Foreword

This book, *The Archaeometallurgy of Iron – Recent Developments in Archaeological and Scientific Research*, brings together the results of archaeological and scientific research into the making and working of iron in antiquity and more recent periods, along with a number of related issues. The main impulse came from the perceived need for the communication and exchange of recent and significant results in these fields among scholars in both western and eastern Europe, and to record the history of archaeometallurgy, the interdisciplinary scientific study which brings together and integrates archaeology, history, cultural anthropology, and materials engineering. At the same time the opportunity is taken to salute the eightieth birthday of Professor Radomír Pleiner, whose contribution to the subject over the past fifty years in the development of this field of research has been unmatched, and whose own researches and initiative have created a firm and abiding bridge between the researchers and the results of their work, not only in eastern and western Europe, but also worldwide. The authors are proud to dedicate this book to Radomír Pleiner.

The Editors

Radomír Pleiner: the magister ferrariarum at 80

Henry Cleere

Radomír Pleiner was a *rara avis* in the early 1960s when we first met. In those days I was working as an editor at the Iron and Steel Institute in London, but I had already become deeply interested in archaeology and had begun studying the subject in my spare time at the London University Institute of Archaeology (now part of University College London). At the suggestion of the then Director of the Institute, Professor W F (Peter) Grimes, I decided to look in depth at the iron industry of protohistoric and Roman Britain. However, I found the literature on early ironmaking was very sparse and so I consulted the late Ronnie Tylecote at Newcastle University. He told me that I should read the work of an archaeologist named Pleiner at the Archaeological Institute in Prague, one of the very few archaeologists working on this neglected field.

When I represented the Iron and Steel Institute at a conference organized by the UN Industrial Development Organization in Prague in 1963 I took the opportunity to seek out Radomír, who invited me to his remarkable office/laboratory in the Letenská basement. Our first expedition together was to look at slag that had been discovered during roadworks in a small Bohemian town, and from there we went to visit his wife's important excavations at Březno. This marked the beginning of a fruitful collaboration and a friendship that has lasted to the present day.

We next met in Prague at the 7th Congress of the International Union of Prehistoric and Protohistoric Sciences (IUPPS/UISPP) in 1966, which saw the birth of the *Comité pour la sidérurgie ancienne* (Ancient Ironmaking Committee). Radomír's energetic and enthusiastic secretaryship of this remarkable international group ever since its creation has made an immense contribution to our understanding of this neglected field of research and fieldwork, once relegated to a secondary role and largely the province of metallurgists and local archaeological amateurs. Its birth was celebrated in great style by a party at Radomír and Ivana's apartment, which brought together veterans such as Kazimiersz Bielenin, Elżbieta Nosek, and Ronnie and Liz Tylecote. At this delightful occasion the new Committee launched what has become a tradition – that of singing songs from many countries (often to the accompaniment of Rado's guitar).

Radomír was born on 26 April 1929: his father Vladimír was a Czech painter and member of the famous Czech Legion, his mother originated

from Russia. He studied prehistory and history at the Faculty of Philosophy of the Charles University in Prague, graduating in 1952, and from 1953 to 1955 he carried out postgraduate work at the Institute of Archaeology of the Czechoslovak Academy of Science, for which he obtained the degree of CSc (equivalent to PhD). An equally significant event during this period was his marriage to fellow archaeologist Ivana in 1955. He was able to continue his researches into the earliest production of iron at the

Figure 1: Radomír Pleiner (right) at the beginning of his career, with Boris Kolchin during smelting experiments in Russia, around 1962. Photo: Archive of Institute of Archaeology RAS Moscow (provided by V. Zavyalov).

Institute. He acquired considerable skills in metallography to facilitate his research on early smithing techniques, and this led to the creation of a metallography laboratory at the Institute in 1963.

From this time onwards Radomír took part in many excavations and experimental work both in Czechoslovakia and abroad, in countries such as Poland, Russia (Fig. 1 /Plate I/), England, Scandinavia, Austria, Germany, and France, as well as contributing widely to symposia and conferences. In 1966–68 he participated in American expeditions to Iran and Afghanistan, and three years later he spent half a year in the USA on an internship. These experiences led to the publication of four studies of ironmaking in the Middle East, which became the subject of the dissertation for which he was awarded the title of Doctor of Science in 1981.

Radomír maintained his connections with the Charles University in Prague: in 1968 he was appointed Docent (Associate Professor) of prehistory and in 1992 he became Professor. He retired in 1993, in the sense that he was no longer in full-time employment, but his research continues. His output of publications is still prodigious: the ASEP Database contains more than forty publications in several languages since 1993, including three classic works, representing the fruits of his many years of research – *The Celtic Sword* (Oxford, 1993), *Iron in Archaeology: The European Bloomery Smelters* (Prague, 2000), and *Iron in Archaeology: Early European Blacksmiths* (Prague, 2006). In recognition of his life's work, which has made a valuable contribution to the development of European science, the former President of the Republic of Poland, Aleksander Kwaśniewski, on 28 April 2005 decorated Radomír Pleiner with the "Knight's Cross of Merit" for his cooperation with the Polish Republic in the field of science (see Fig. 2 /Plate II/).

It would be no exaggeration to assert that the study of ancient ironmaking owes the high level of esteem that it commands in the academic world of archaeology at the present time to Radomír Pleiner. His research and the dissemination of the results of that research have been exemplary, and he has inspired many young archaeologists to enlarge and refine our knowledge of the making and working in antiquity of iron and to demonstrate its immense significance in the development of human societies. At the same time he has been the most generous of scholars, willing to share his ideas and his results with colleagues and students alike. And most of all he has been the most warm, welcoming, steadfast, and entertaining friend. It has been a conceit of his for many years to complain lugubriously and sonorously that "I am an old man" – often described by his family and friends as proof of his Russian genes. This is, of course, nonsense: at eighty he is as young in heart and mind as ever.

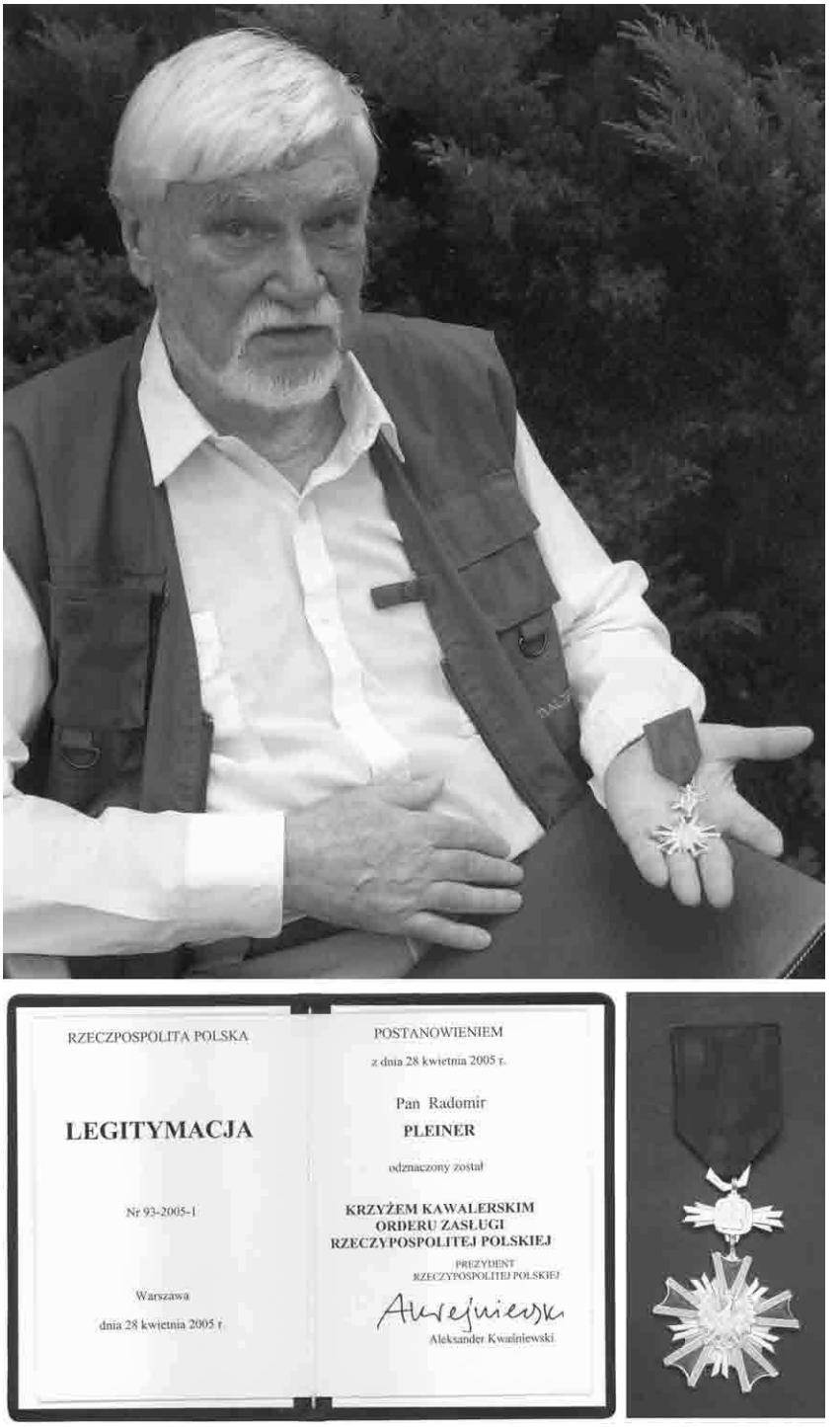

Figure 2: Radomír Pleiner and the Knight's Cross of Merit of the Republic of Poland. Photo from the Pleiner family archive.

List of R.Pleiner's publications

Books

Výroba železa ve slovanské huti u Želechovic na Uničovsku (Praha: ČSAV) – 1955, 54 p.

Základy slovanského železářského hutnictví v českých zemích. Vývoj přímé výroby železa z rud od doby halštatské do 12. věku (Praha: ČSAV) – 1958, 335 p.

Staré evropské kovářství – stav metalografického výzkumu (Praha: ČSAV) – 1962, 332 p. [sum. German].

Iron Working in Ancient Greece (Praha: Národní technické muzeum) – 1969, 55 p. [sum. German].

Přehled vývoje starého železářství v českých zemích (Praha: TEVÚH) – 1972, 61 p. (with J. Kořan).

Pravěké dějiny Čech (Praha: Academia) – 1978, 872 p. [sum. German] (with A. Rybová, eds.).

Otázka státu ve staré Galii (Praha: Academia) – 1979, 111 p.

Dějiny hutnictví železa v Československu. Od nejstarších dob do průmyslové revoluce (Praha: Academia) – 1984, 296 p. (with J. Kořan, M. Kučera & J. Vozár) [sum. Russian, German].

The Celtic Sword (Oxford: Clarendon Press) – 1993, 196 p.

Minilexikon k dějinám lodí a námořní plavby (Praha: Naše vojsko) – 1994, 245 p.

Iron in Archaeology: The European Bloomery Smelters (Praha: Archeologický ústav AV ČR Praha) – 2000, 400 p.

Iron in Archaeology: Early European Blacksmiths (Praha: Archeologický ústav AV ČR Praha) – 2006, 379 p.

Articles

– 1950

'Neandertálský pohřeb v jeskyni Tešik-Taš (již. Uzbekistan)', *Příroda* 44 – 1951, 95.

'Problém druhotného zpracování vytaveného železa v pravěku', *Archeologické rozhledy* 4 – 1952, 511-519, 554-555, 558-559 [sum. French].

'Využití chemických a spektrálních analýz při studiu pravěké metalurgie', *Archeologické rozhledy* 5 – 1953, 780-784, 789-796, 836, 843 [sum. French].

'Železářská dílna z mladší doby hradištní ve sklepení Betlémské kaple', *Památky archeologické* 44 – 1953, 369-388 [sum. Russian, German].

'Železářské objekty ve sklepení Betlémské kaple v Praze', *Archeologické rozhledy* 5 – 1953, 646-653, 657-659, 708, 716, 717 [sum. French].

'Slovanská soustava železářských pecí v Želechovicích u Uničova', *Archeologické rozhledy* 6 – 1954, 196-200, 203-205, 209 [sum. French].

'Tuchlovice I - nové sídliště z doby římské na Kladensku', *Archeologické rozhledy* 6 – 1954, 765-767, 776-783, 834, 840 [sum. French].

– 1955

'Výzkum železárny na sídlišti Tuchlovice I', *Archeologické rozhledy* 7 – 1955, 200-208, 213-215, 277, 285 [sum. French].

'Pozdně laténská železárna v Kostomlatech u Nymburka', *Archeologické rozhledy* 7 – 1955, 628-632, 633, 641 až 643, 710, 716-717 [sum. French].

'Zjišťovací výzkum železárny na římském sídlišti Tuchlovice 1, okr. N. Strašecí r.1953-1954', in *Referáty Liblice 1954* – 1955, 2.

'Laténská hutnická technika jako základ středoevropské železné civilizace', in *Referáty Liblice 1955*, I – 1956, 92-101. [sum. German].

'Poznámky k výrobní technice staroslovanských čepelí', *Památky archeologické* 47 – 1956, 314-334. [sum. German] (with F. Plzák & O. Quadrát).

'État des fouilles relatives à la production ancienne du fer en Tchécoslovaquie et autres pays slaves', *Techniques et Civilisations V*(4) (St. Germain-en-Laye) – 1956, 113-128.

'Domácí pec z doby římské v Libici n. Cidl.', *Archeologické rozhledy* 9 – 1957, 168-175, 192 [sum. French].

'Stuttgartská metoda hodnocení spektrálních analýz nejstarších kovů a její význam pro prehistorii', in *Referáty Liblice 1957* –1958, 47-54 [sum. German].

'Die Ergebnisse neuer Ausgrabungen an vor-u. frühgeschichtlichen Eisenhüttenplätzen in Böhmen und Mähren', in *Stahl und Eisen* 78 – 1958, 1748-1754.

'Hrob lidu se šňůrovou keramikou z Lovosic', *Archeologické rozhledy* 10 – 1958, 172-178, 192-193 [sum. German].

'Metalografie a studium kovářských technik v archeologii', *Referáty Liblice 1958* – 1959, 70-78 [sum. German].

'Úvaha o halštatsko-laténské sídlištní keramice severozápadních Čech. Podle nálezu chaty v Dobříčanech u Žatce', *Památky archeologické* 49 – 1958, 119-142 [sum. German].

'Bylanské knížecí hroby v Lovosicích', *Archeologické rozhledy* 11 – 1959, 653-660, 669-673 [sum. German].

'Metallographische Untersuchungen von vor- u. frühgeschichtlichen eisernen Gegenständen aus der Tschechoslowakei', in *Stahl und Eisen* 79 – 1959, 294-298.

'Problémy rekonstrukce pravěkých pecních staveb', in *Filipův sborník Acta Univ. Carol.* 3 (Praha) – 1959, 225-232 [sum. German].

– 1960

'Význam typologie železářských pecí v době římské ve světle nových nálezů z Čech', *Památky archeologické* 51 – 1960, 184-220, [sum. German].

'Středověká výroba dřevného dehtu v Krásné dolině u Rakovníka', in *Referáty Liblice 1959* I – 1960, 115-123.

'Experiment v archeologii', *Památky archeologické* 52 – 1961, 616-622 [sum. German].

'K problémům československého pravěku', *Archeologické rozhledy* 13 – 1961, 520-570 [sum. French] (with B. Soudský et al.).

'Středověké dehtárny v Krásné Dolině u Rakovníka', *Archeologické rozhledy* 13 – 1961, 197-200, 202-213, 217-218 [sum. German].

'Zpráva o pokusech s primitivním tavením železa v rámci československo-polské akce', in *Referáty Liblice 1960* – 1961, 65-73 [sum. German].

'Železářská pec římského období v Luštěnicích u Ml. Bosleslavi', *Archeologické rozhledy* 13 – 1961, 483-492, 500-502 [sum. German].

'Stav výzkumu nejstarších dějin železářské techniky', in *Zprávy Komise pro dějiny přír., lékařských a technických věd při hist. sekci ČSAV* 8 (Praha) – 1961, 5-14.

'Slovanské sekerovité hřivny', *Slovenská Archeológia* 9 – 1961, 401-450 [sum. German].

'Modely z umělých hmot', *Archeologické rozhledy* 14 – 1962, 547-552, 557-564 [sum. German] (with S. Frydrýn).

'Tvrzení břitů v kovářské technice pravěku a středověku', in *Rozpravy NTM* 5 – 1962, 20-34.

'Polsko-czechoslowackie doświadczenia wytopu żelaza w dymarkach z okresu rzymskiego', *Kwartalnik Hist. Nauki i Techniky* 7(3) – 1962, 307-320 (with M. Radwan).

'La sidérurgie dans les pays tchèques au moyen âge', *Revue d'histoire de la sidérurgie* 3 (Nancy), – 1962-1963, 179-195.

'Nejstarší dějiny národa českého a slovenského', *Věstník ČSAV* 3 – 1963, 384-385 (with Z. Smetánka).

'Polnisch-tschechoslowakische Schmelzversuche in den Rennöfen der römerzeitlichen Bauarten', *Archeologické rozhledy* 15 – 1963, 47-71 [sum. Czech] (with M. Radwan).

'Pozoruhodná technika Velkomoravskej ríše', *Technické noviny* IX, č. 36, 3. 9. (Bratislava) – 1963.

'Rediscovering the Techniques of Early European Blacksmiths', *Archaeology* 16, No. 4 – 1963, 234-242.

'Schmelzvesuche mit einem slawischen Schachtofen in Novgorod 1961. Nachtrag', *Archeologické rozhledy* 15 – 1963, 62-64, 68-71.

'Hrnčířství - nástin výroby', *Zprávy ČSSA* 6(4) – 1964, 32.

'Konference o počátcích feudalismu na Slovensku, Smolenice 1963', *Archeologické rozhledy* 16 – 1964, 293-294.

'Symposium o primitivním hutnictví železa ve Švédsku, 1963', *Archeologické rozhledy* 16 – 1964, 594.

– 1965

'Bericht über die metallkundliche Untersuchung zweier Eskimo-Werkzeuge', in *Abhandlungen und Berichte des Staatlichen Museums für Völkerkunde Dresden* 24 – 1965, 5-35.

'Mutějovice, okr. Rakovník. Sídliště z mladší doby hradištní a ze středověku. Výzkumy system. a expedice', *Bulletin záchranného oddělení AÚ ČSAV* 3 1965, – 1966, 68-70.

'Orientační marginálie, chronologická řada a tematická řada', *Archeologické rozhledy* 17 – 1965, 114-115; 18, 1966, 77-78 [sum. French, German] (with J. Hrala).

'Poznámky k výrobě měděné a bronzové industrie', *Zprávy ČSSA* 7(1) – 1965, 5.

'Technologie kovářství a dehtařství', in *O počiatkoch slovenských dejín* (Bratislava) – 1965, 96-103.

'Výroba zemědělských nástrojů na Velké Moravě', in *Velká Morava, almanach* 65 (Brno) – 1965, 130-133.

'Przyczynek do problemu metalurgii wczesnohistorycznej i zagadnienia tak zwanego metalu świętokrzyskiego', *Kwartalnik Hist. Nauki i Techniky*

10(1-2) – 1965, 19-42.

'Die Eisenverhüttung in der 'Germania Magna' zur römischen Kaiserzeit, 45', in *Bericht der Röm.-Germ. Kommission 1964* 45 (Berlin) – 1965, 11-86.

'Untersuchungen an Klingen eiserner Latèneschwerter', in *Technische Beitrage zur Archäologie* 2 (Mainz) – 1965, 38-51, tab. 11-18 (with E. H. Schulz).

'Untersuchungen von Baustoffen und Schlacken aus den frühgeschichtlichen Rennöfen Böhmens und Mährens', in *Technische Beiträge zur Archäologie* 2 (Mainz) – 1965, 1-37 (with M. Bartuška).

'Das Eisenhüttenwesen bei den Slawen im frühen Mittelalter', in *Vita pro ferro, Festschrift f. R. Durrer* (Schaffhausen) – 1965, 135-162.

'Americká expedice s čs. účastí v Iránu (1966)', *Archeologické rozhledy* 20 – 1968, 255-256 [sum. German].

'Recherches sur les débuts de la sidérurgie', in *Investigations archéol. en Tchécoslovaquie* (Prague) – 1966, 292-296.

'Neue Beiträge der tschechoslovakischen Archäologie zur Geschichte des Eisenhüttenwesens in Europa', in *Atti del VI. Congresso UISPP III.* (Roma: Sezioni V-VIII) – 1966, 70-74.

'Otázka přímé výroby ocele v protohistorické technice', *Kovové materiály* IV (Bratislava) – 1966, 208-220 [sum. Russian, German, English].

'Gewinnung und Bearbeitung des Eisens in Grossmähren', in *'Grossmähren', Ausstellung der ČSAV in Mainz 1966*, 75-79. Austellungskatalog in Wien 1966, 75-79.

'Pokusné tavby v protohistorických pecích', *Zprávy Spol. pro dějiny věd a techniky* 3 – 1966, 65.

'Sépultures princières de Lovosice (Bohême)', in *Investigations archéol. en Tchécoslovaquie* (Prague) – 1966, 178-179.

'Die Technologie des Schmiedes in der grossmährischen Kultur. Kovářská technologie Velké Moravy', *Slovenská Archeológia* 15 – 1967, 77-188.

'The Beginnings of the Iron Age in Ancient Persia', *Annals of the Náprstek Museum* 6 (Praha) – 1967, 9-72.

'Preliminary Evaluations of the 1966 Metallurgical Investigations in Iran', in J. R. Caldwell (ed.) *Investigations at Tal-i-Iblis* (Springfield Ill: Illinois State Museums Reports 9) – 1967, 340-405.

'Želechovice près d'Uničov (Moravie)', *Investigations archéol. en Tchécoslovaquie* (Prague) – 1966, 240-241.

'Preliminary Reports of the Metallurgical Project', in J. R. Caldwell (ed.) *Investigations at Tal-i-Iblis* (Springfield Ill: Illinois State Museums Reports 9) – 1967, 318-326 (with C. S. Smith & T. A. Wertime).

'Metallkundliche Untersuchungen der Messerklingen von der frühslawischen Siedlung in Dessau-Mosigkau', in B. Krüger, *Dessau-Mosigkau* (Berlin) – 1967, 176-189, 20 tah.

'O metodzie identifikacii żelaza w znaleziskach archeologicznych. Uwagi na ternat polemiki z doc. J. Piaskowskim', *Kwartalnik Historii Nauki i Techniki* 12(1) – 1967, 111-120.

'Schmiedetechnik der Hallstattzeit im Lichte der Untersuchung des Hortfundes von Schlöben', *Archeologické rozhledy* 20 – 1968, 33-42, 139-140 [sum. Czech].

'The Iron Age in Subsaharan Africa, referát z Current Anthropology, Oct. 1966', *Archeologické rozhledy* 20 – 1968, 278.

'Archaeological and metallurgical investigations in the Central Kerman Range, Southeastern Iran (Illinois State Museum Project)', *Archeologické rozhledy* 20 – 1968, 524.

'Le travail de forgeron comme expérience', *Archeologické rozhledy* 20 – 1968, 525.

'Untersuchungen der Schlackenproben von Mühlthal', in K. Dannheimer, *Epolding-Mühlthal* (München) – 1968, 97-101.

'Iron smelting experiments in protohistoric furnaces in Březno', in *Actes du XIe Congrès d'histoire des sciences* VI (Wroclaw-Varsovie-Cracovie)

– 1968, 163-167.

'Experimental Smelting of Steel in Early Medieval Furnaces', *Památky archeologické* 60 – 1969, 458-487.

'La datation du fer par la méthode C14', *Archeologické rozhledy* 21 – 1969, 245.

'Středověké sídliště s kovárnami u Mutějovic', *Památky archeologické* 60 – 1969, 533-571 [sum. German].

'Les travaux analytiques sur les scories de la sidérurgie étrusque et islamique', *Archeologické rozhledy* 21 – 1969, 825.

'Les travaux progressifs au laboratoire de l'Institut archéologique à Prague', *Archeologické rozhledy* 21 – 1969, 553.

'Proměny v ekonomickém hodnocení železa v počátcích jeho historie', in *Z dějin hornictví a hutnictví* (Rozpravy NTM 39) – 1969, 25-35. [sum. English, German].

'Le groupe de recherches sur la sidérurgie ancienne au Danemark', *Archeologické rozhledy* 21 – 1969, 243.

'Musée du fer à Nowa Słupia, Pologne', *Archeologické rozhledy* 21 – 1969, 243.

'La sidérurgie en Grèce Ancienne', *Archeologické rozhledy* 21 – 1969, 245.

'Investigations métallographiques des objets romains de Prähistorische Staatsammlung Munich', *Archeologické rozhledy* 21 – 1969, 246.

'National Geographic Society and Smithsonian Institution pyrotechnological expedition in Afghanistan, Iran and Turkey 1968', *Archeologické rozhledy* 21 – 1969, 552-553.

'Le problème de l'origine de l'âge du fer en Inde', *Archeologické rozhledy* 21 – 1969, 825.

'Theory and methodology in archaeological interpretation, Flagstaff, Ariz. 1968', *Archeologické rozhledy* 21 – 1969, 552.

'Une conférence sur l'évaluation des trouvailles concernant la métallurgie

à Haithabu', *Archeologické rozhledy* 21 – 1969, 243-244.

– 1970

'Cín v počátcích civilizace', in *Rozpravy NTM* 43 (Praha) – 1970, 39-52 [sum. English, German].

'Evidencing accounts of technological monuments in archaeology and history', in *Actes du VIIe Congrès de UISPP à Prague 1966* (Praha) – 1970, 88-91.

'Les fouilles d'un atelier sidérurgique de la période de La Tène à Mšec, Bohême occidentale', *Archeologické rozhledy* 22 – 1970, 353 (with M. Princ).

'La réduction du fer par la méthode directe', *Archeologické rozhledy* 22 – 1970, 609-610.

'Středověká výroba smoly v Krásné dolině u Rakovníka', *Památky archeologické* 61 – 1970, 472-518. [sum. German].

'Přírodovědné metody v archeologii', *Vesmír* 49 – 1970, 292-295.

'Zur Schmiedetechnik im römerzeitlichen Bayern', *Bayerische Vorgeschichtsblätter* 35 – 1970, 113-141.

'Untersuchung eines Kurzschwertes des luristanischen Typus', *Arch. Anzeiger* 84 – 1969 (1970), 41-47.

'Archeologický výzkum středověkých železáren u Radětic', in *Vlast. sb. Podbrdska V* – 1971, 42-63 [sum. German].

'Die Kelten und keltischen Oppida in Mitteleuropa und im Karpatenhecken, Liblice 1970', *Archeologické rozhledy* 23 – 1971, 335.

'La 34e session du 'Geschichtsausschuss des Vereines deutscher Eisenhüttenleute', Bochum-Querenburg 1970", *Archeologické rozhledy* 23 – 1971, 335.

'Středověká islámská výroba u Hannashqu, Persie', in *Z dějin hutní výroby* (Rozpravy NTM 47) – 1971. 8-16.

'Untersuchung einer Eisenschlacke aus Haithahu', in *Berichte über die*

Ausgrabungen (Neumünster) – 1971, 110-112 (with J. Pelikán & M. Bartuška).

'Zur Schmiedetechnik des Grossmahrischen Reiches. Jerzy Piaskowski und die Deutung der metallographischen Befunde von Eisenfundstücken', *Acta Archaeologica Carpathica* 12 – 1971, 107-125 [sum. Polish].

'The Problem of the Beginning Iron Age in India', *Acta Praehist. et Archaeol.* 2 – 1971, 5-36.

'Der Handel mit Eisen im östlichen Mitteleuropa im 4. bis 9. Jahrhundert', *Antikvariskt arkiv* 40 (Early medieval studies 3) – 1971, 13-21.

'Počátky civilizace železa ve staré Asýrii', in *Z dějin hutnictví* (Rozpravy NTM 55) – 1972, 7-15 [sum. German, English].

'Věda o tom, co bylo', *Svět práce* 13. 12. – 1972.

'Die Schmelzversuche in der Methodik der Erforschung des Rennverfahrens', in W. U. Guyan, R. Pleiner & R. Fabešová (eds.), *Versuchschmelzen und ihre Bedeutung f. die Metallurgie des Eisens u. dessen Gesch.* (Schaffhausen, Prag) – 1973, 1-5.

'Der Einfluss der Ofenkonstruktion auf die Aufkohlung von Eisen im Rennofen', in *Versuchschmelzen und ihre Bedeutung f. die Metallurgie des Eisens u. dessen Gesch.* (Schaffhausen, Prag) – 1973, 17-24.

'Mezinárodní symposium Helgö II., 'Frühmittelalterliche Metallwerkstätten und Kunsthandwerk im Germanischen Raum', Hässelby bei Stockholm 1972', *Archeologické rozhledy* 25 – 1973, 228-229, 455.

'Symposium 'Doznievanie laténskej civilizácie a začiatky germánskeho osídlenia nad stredným Dunajom', Malé Vozokany 1972', *Archeologické rozhledy* 25 – 1973, 227-228.

'The famous Hallstatt Iron Ring from Býčí skála, Moravia and its Metal', *Archeologické rozhledy* 25 – 1973, 696.

'Několik poznámek k článku J. Kruliše 'Mohla se výroba železa vyvinout z kovohutnictví?' ', in *Studie z dějin hornictví* 4 – 1973, 63-68 [sum. German].

'Metallography of Early Artifacts: the Problem of Welding Together Iron and Steel', *Antikvariskt arkiv* 53 (Early Medieval Studies 6), 1973, 17-28.

'K otázce jakosti keltských zbraní na základě hrobového nálezu z Třebohostic', *Archeologické rozhledy* 26 – 1974, 461-467, 555-559 [sum. German].

'Technika za přisvojovacího a nejstaršího výrobního hospodářství (od osídlení do 10. st.)', in *Dějiny techniky v Československu* (Praha) – 1974, 23-60.

'Technika v období pravěku', in *Dějiny techniky za feudalismu* (Rozpravy NTM 60), – 1974, 11-20 [sum. German, English].

'Nochmals zu J. Piaskowski's Erkennungsmerkmalen der alten Schmiedetechnik von Eisenfundstücken', *Acta Archaeologica Carpathica* 14 – 1974, 151-154 [sum. Polish].

Berghau, D.: *Eisenerz*, Heslo, in *Reallexikon der Germ. Altertumskunde*, Bd. 2 (Berlin-New York) – 1974, 258-261.

'The Assyrian Iron Age: The History of Iron and the Assyrian Civilization', in *Proceedings of the American Philosophical Society* 118 – 1974, 284-313. (with J. K. Bjorkman).

– 1975

'Hutnictví železa v badatelském programu Archeologického ústavu ČSAV v Praze', *Archeologické studijní materiály* 10/2 (Praha) – 1975, 100-108, 178-179 [sum. English].

'Ivo Kruliš a Ladislav Jeníček v dějinách hutnictví', in *Z dějin hutnictví 2* (Rozpravy NTM 66) – 1975, 11-16 [sum. German, English].

'Počátky šachtové pece v evropském pravěku', in *Z dějin hutnictví 2* (Rozpravy NTM 66) – 1975, 77-84 [sum. German, English].

'Die Aussagen der Eisenmetallurgie für die archäologisch-historische Forschung', in *Moderne Probleme der Archäologie* (Berlin) – 1975, 189-198.

'Eisenschmiede im frühmittelalterlichen Zentraleuropa. Die Wege zur Erforschung eines Handwerkzweiges',*Frühmittelalterliche Studien* 9

(Münster/W.) – 1975, 79-92.

'The Beginning of the State among Continental Celts during the Late La Tène period', in *IXe Congrès préhistorique de UISPP à Nice 1976, Section VIII* 2, – 1976, 573.

'Struska ze železárny v Dubči a její výpověď o hutnickém pochodu', *Archeologické rozhledy* 28 – 1976, 276-278 [sum. German].

'Halštatský nůž z Tišic a jeho technologie', in *Studie Okresního muzea Praha-východ* – 1976, 6-14.

Prehľad vývoja železiarstva na Slovensku do roku 1918, Košice 1976. [sum. Russian, German, English], (with J. Vozár & M. Šuradejová).

'Nachbildung einer spätkaiserzeitlichen wurmbunten Schwertklinge aus Nordostböhmen', in *Festschrift Richard Pittioni* II (Wien: Arch. Austriaca, Beiheft 14) – 1976, 130-141.

'II. Congrès international de Thracologie (Bucarest 1976)'. *Archeologické rozhledy* 29 – 1977, 321-322

'Ancient Production of Iron in the Scientific Programme of the IXth Congress of the UISPP, Nice 1976', *Archeologické rozhledy* 29 – 1977, 321.

'Extensive Eisenverhüttungsgebiete im freien Germanien', in *Symposium Ausklang der Latènezivilisation und Anfänge der germanischen Besiedlung im mittleren Donaugebiet* (Bratislava) – 1977, 297-305.

'Metallographical Study of La Tène Period Iron Swords', *Archeologické rozhledy* 29 – 1977, 323.

'Nové výzkumy k počátkům hutnictví železa v Československu', in *Z dějin hutnictví* 4 – 1977, 7-12 [sum. German, English].

'Neue Grabungen frühgeschichtlicher Eisenhüttenplätze in der Tschechoslowakei und die Bedeutung des Schachtofens für die Entwicklung des Schmelzvorganges', *Wissenschaft1iche Arbeiten aus dem Burgenland* 59 (Eisenstadt) – 1977, 107-117.

'Jan Kořan a počátky českého železářství (70. narozeniny)', in *Studie z dějin hornictví* 8 (Rozpravy NTM 70) – 1978, 18-19 [sum. German,

English].

'Rozbor vzorků železa z doby hradištní z hutí u Olomučan', in *Sb. OM Blansko* 10 – 1978, 16-22.

'Romano-Barbarian settlement with bloomeries at Ořech, near Prague', *Archeologické rozhledy* 31 – 1979, 316-317 (with K. Motyková).

'Excavations of Slav bloomeries at Olomučany (Moravie) continued', *Archeologické rozhledy* 31 – 1979, 317 (with V. Souchopová).

'Die Technik des Schmiedehandwerks im 13. Jahrhundert im Dorf und in der Stadt', *Vorträge u. Forschungen* 22 (Sigmaringen) – 1979, 399-410.

'The Technology of Three Assyrian Iron Artifacts from Khorsabad', *Journal of Near Eastern Studies* 38 – 1979, 83-91.

'K vývoji slovanské nožířské techniky v Čechách', *Archeologické rozhledy* 31 – 1979, 245-256, 354-360 [sum. German].

– 1980

'Ad multos annos. Akademiku Josefu Poulíkovi k 70. narozeninám.' *Památky archeologické* 71 – 1980, 5-9.

'Konference 'Experimental Archaeology', London 1980', *Archeologické rozhledy* 32 – 1980, 649-650.

Přehled dějin Československa I, 1, 'kap. 1-5.' (Praha) – 1980, 49-99 (with J. Poulík, D. Bialeková & Č. Staňa).

'Early Iron Metallurgy in Europe', in Th. A. Wertime and D. Muhly (eds.) *'The Coming of the Age of Iron'* (New Haven-London: Yale Univ.) – 1980, 375-415.

'Zur Technik der Säbel aus den slawisch-awarischen Gräberfeldern der Südslowakei', in *Rapports du IIIe Congrès d'Archéologie Slave* 1 (Bratislava) – 1980, 625-627.

'Chemické analýzy ve výzkumu nejstaršího železářství', in *Bulletin záchranného oddělení AÚ ČSAV 1975, Supplementum* (Praha) – 1981, 78-84.

'K aplikaci chemie v archeologii', *Bulletin záchranného oddělení AÚ ČSAV*

1975, Supplenlentum (Praha) – 1981, 77-78, 84-93, tab. 1-5 (with M. Soudný).

'Kovářská technika na keltských oppidech', in *Současné úkoly čsl. archeologie, Valtice 1978* (Praha-Brno) – 1981, 99-101 [sum. Russian, German].

'Blšany, okr. Louny', in *Bulletin záchranného oddělení AÚ ČSAV 1976-1977* 12 – 1981, (with I. Pleinerová).

'Einführung, in Frühes Eisen in Europa', in *Acta des 3. Symposiums des Comité pour la sidérurgie ancienne de UISPP, Schaffhausen-Zürich 1979* (Schaffhausen) – 1981, p. 20.

'Die Wege des Eisens nach Europa", in *Frühes Eisen in Europa* (Schaffhausen) – 1981, 115-128.

'Metallography of La Tène period iron implements from the Celtic oppida', in *Nouvelles archéol. dans la Rép. soc. tchèque* (Prague-Brno) – 1981, 106-107.

'Interdisciplinary approaches in the Czechoslovak archaeology', in *Nouvelles archéol. dans la Rép. soc. tchèque* (Prague-Brno) – 1981, 225-231.

'Osobnost a dílo Sydneye Gilchrista Thomase', *Z dějin hutnictví* 9 – 1981, 209-214 [sum. German, English].

'Untersuchungen zur Schmiedetechnik auf den keltischen Oppida', *Památky archeologické* 73 – 1982, 86-173 [sum. Czech, Russian].

'Die Herstellungstechnologie der germanischen Eisenwerkzeuge und Waffen aus den Brandgräberfeldern der Südwestslowakei', *Slovenská Archeológia* 30 – 1982, 78-121 [sum. Russian].

'Vznik státu v keltském prostředí', in *Metodologické problémy čsl. archeologie* (Praha) – 1982, 55-59, [sum. German].

'Techniky kovářské výroby', in M. Richter *Hradišťko u Davle* (Praha: Academia) – 1982, 298-300, tab. 40-67 [sum. German, English].

'The Beginnings of Metallurgy on the Territory of Czechoslovakia', in *Bull. of the Metals Museum* 7 – 1982, 16-28 (with D. Bialeková).

'Třicet let archeometalurgického výzkumu k dějinám železa v Československu', *Dějiny věd a techniky* 83, roč. 16 – 1982, 97-113.

'Untersuchungen zur frühen Eisenverhüttung', *Das Altertum* 28 – 1982, 49-57 [sum. English].

'Počátky železa v civilizaci lidstva', *Vesmír* 61 – 1982, 145-151.

'7th Monothematic Spring Seminar of the Metallurgical Board of the Club of the National Technical Museum at Prague, 1983', *Archeologické rozhledy* 35 – 1983, 683.

'Conference of the Comité scientifique pour la promotion de l'Archéologie en Bourgogne', *Archeologické rozhledy* 35 – 1983, 682-683.

'International Symposium 'Siedlung, Wirtschaft und Gesellschaft während der jüngeren Bronze- u. Halstattzeit in Mitteleuropa', Potsdam-Cecilienhof 1983', *Archeologické rozhledy* 35 – 1983, 683.

'Journées de paléométallurgie, Compiègne, Fr. 1983', *Archeologické rozhledy* 35 – 1983, 682.

'Metalografický výzkum železného srpu a sekery z mostecké studně', *Památky archeologické* 75 – 1983, 498-502 [sum. German].

'Experimental bloomery smelts at Blansko, Czechoslovakia, in 1982', *Archeologické rozhledy* 35 – 1983, 333.

'Forging of La Tène Period Iron Swords', *Archeologické rozhledy* 35 – 1983, 684.

'Neue Entdeckungen von römerzeitlichen Eisenhütten in den böhmisch-mährischen Siedlungsräumen', *Offa* 40 – 1983, 63-68 [sum. English].

'Zur Technik von Messerklingen aus Haithabu', in *Berichte über die Ausgrabungen in Haithabu* 18 – 1983, 63-92, 15 tab.

'Die latènezeitliche Eisenverhüttung und die Untersuchung einer Rennschmelze in Mšec, Böhmen', *Památky archeologické* 75 – 1984, 133-180 (with M. Princ).

'Počátky slovanského osídlení 6.-7. stol, teze I/4; Změny v zemědělské výrobě-řemesla, obchod, teze II/2; Počátky českého státu (konec 9.-10. stol.): teze III/6; Časně feudální stát Přemyslovců (11.-12. stol.); teze IV/5', in *Čechy v době slovanské, archeologie o vzniku a počátcích českého státu. Teze* (Praha: AÚ ČSAV) – 1984, 16-24, 42-46, 98-116, 148-164.

'Několik poznámek k vývoji cen železa od dob jeho objevení do počátku středověku', *Z dějin hutnictví* 12 – 1984, 215-221 [sum. German, English].

'Závěr kolokvia o problémech laténské numizmatiky', *Slovenská numizmatika* 8 – 1984, 183-188 [sum. Russian, German].

– 1985

'Komentář k výsledkům rozborů hutnických materiálu ze železáren v Chýnici', *Archeologické rozhledy* 37 – 1985, 177-180 [sum. German].

'The bloomeries of the Romano-Barbarian period at Varín, North Slovakia', *Archeologické rozhledy* 37 – 1985, 467.

'Úloha empirie v nejstarší železářské technice', *Z dějin hutnictví* 13 – 1985, 204-210 [sum. German, English].

'Schmiedetechnik aus den mitteleuropäischen keltischen Oppida', in *Produktivkräfte u. ProduktionsverhaItnisse in ur- u. frühgeschichtlicher Zeit* (Berlín) – 1985, 227-230.

'Komentář k výzkumu železných strusek z archeologických nálezů', *Archeologické rozhledy* 38 – 1986, 522-524 [sum. English].

'Experimental pottery firing at the expedition at Březno, 1984', in *Archaeology in Bohemia 1981-1985* (Prague) – 1986, 301-306.

Archeology in Bohemia 1981-1985 (Prague) – 1986 (Pleiner R. & Hrala J. eds.).

'Eisen, Eisenverhüttung, Hesla', in *Reallexikon der Germ. Altertumskunde* Bd. 7 (Berlin - New York) – 1986, 60-66.

'Poznámky k chemickému a mineralogickému složení dýmařských strusek z Blanenska', *Studie AÚ ČSAV Brno* 13, č. 1 – 1986, 98-102 (with M.

Bartuška).

'Über das Eisen der Bronzezeit', in *Veröffentlichungen des Museums für Ur- und Frühgeschichte Potsdam* 20 – 1986, 237-240.

'Eine eingetiefte Eisenverhüttungswerkstatt der älteren römischen Kaiserzeit in Lovosice', *Archeologické rozhledy* 39 – 1987, 75-89, 111-116 [sum. Czech] (with V. Salač).

'Smelting experiments at Blansko 1986', *Archeologické rozhledy* 39 – 1987, 342.

'The International Symposium 'Archaometallurgie von Kupfer und Eisen in Westeuropa', Mainz 1986', *Archeologické rozhledy* 39 – 1987, 341.

'Brennversuche in einem nachgebildeten slawischen Töpferofen', *Slovenská Archeológia* 36 – 1988, 299-308 [sum. Russian].

'Zum Eisenerzbergbau im frühen Europa', in *Surowce mineralne w pradziejach i we wczesnym średniowieczu Europy Środkowej* (Wrocław, Warszawa, Kraków, Gdańsk, Łódź) – 1988, 53-61.

'Les débuts de la métallurgie du fer chez les Celtes', in *Les Princes Celtes et la Méditerranée* (Paris) – 1988, 179-185.

'Mezinárodní sympozium Archaeometallurgy of iron: Results achieved 1967-1987', *Věstník ČSAV* 97 – 1988, 226-230.

'Expérimentation en archéologie: Bilan et perspectives', *Archeologické rozhledy* 41 – 1989, 213.

'K otázce funkce a rozšíření sekerovitých hřiven - Zur Frage der Funktion und Verbreitung der Axtbarren', *Slovenská numizmatika* 10 – 1989, 81-88.

'1967-1987: The activity of the Comité pour la sidérurgie ancienne de l'UISPP', in R. Pleiner (ed.), *Archaeometallurgy of Iron 1967-1987* (Prague) – 1989, 5-8.

'Iron-Making and -Working on the territory of Czechoslovakia until middle ages (Recent results)', in R. Pleiner (ed.), *Archaeometallurgy of Iron 1967-1987*, (Prague) – 1989, 93-107.

– 1990

'The International Symposium 'Archaeometallurgy of Iron: from Bloom to Knife' ", *Archeologické rozhledy* 42 – 1990, 308-309.

'Die Technologie eines frühmittelalterlichen Schwertes aus Varín, Slowakei - Metalografie časně středověkého meče z Varína', *Archeologické rozhledy* 42 – 1990, 674-679, 732-734.

'The Technology of Medieval Blacksmiths in Prague', in *Dal basso fuoco all'altofomo* (Brescia) – 1991, 78-82.

'Symposium 'Experimentelle Archäologie in Deutschland' ", *Archeologické rozhledy* 43 – 1991, 317-318.

'Die Schmiede im mittelalterlichen Prag. Die Eisengegenstände aus der Notgrabung am Wenzelsplatz', *Archaeologica Pragensia* 11 – 1991, 187-237. (with V. Huml).

'Die Technik der Schmiede im mittelalterlichen Prag - Technika kovářů středověké Prahy', *Archaeologica Pragensia* 11 – 1991, 239-287.

'Bemerkungen zu einigen Schmelzversuchen in frühmittelalterlichen Rennöfen in der Tschechoslowakei', in *Experimentale Archäologie* (Oldenhurg) – 1991, 323-329.

'Experimental firing of pottery in a model of an Early Medieval updraught kiln at Březno, Czechoslovakia', in *Archéologie expérimentale, T. I, Le feu: le métal, la céramique. Actes du Colloque International 'Expérimentation en archéologie: Bilan et Perspectives'* (Paris) – 1991, 232-236.

'Spätkaiserzeitliche und völkerwanderungszeitliche Stahlklingen aus Nordwestböhmen im Lichte der Metallographie', in *Jahrbuch des Römisch-Germanischen Zentralmuseums Mainz* 35 – 1988 (1991), 602-610.

'Study of the early production of iron in Czechoslovakia 1985-1989', in *Archaeology in Bohemia 1986-1990* (Praha) – 1991, 252-255.

'Professor Ronald Tylecote. A reminiscence', *Historical Metallurgy* 25 – 1991, 4-5.

'Die Technologie der Messerherstellung in der frühmittelalterlichen Für-

stenburg von Budeč, Böhmen - Technologie výroby nožů na časně středověkém knížecím hradě na Budči, Čechy', *Památky archeologické* 84 – 1993, 69-92 [sum. Czech].

'Punch Marks on High Medieval Iron Artefacts', in *Bloomery Ironmaking during 2000 Years III* (Trondheim) – 1993, 79-89 (with V. Huml).

'Examination of some late Hallstatt and La Tène period knives', in J. Waldhauser u. A., *Die hallstatt- und latènezeitliche Siedlung mit Gräberfeld bei Radovesice in Böhmen II* (Gutachten, Praha) – 1993, 178-182.

'The technology of ironmaking in the bloomery period - a brief survey of archaeological evidence', in R. Francovich (ed.), *Archeologia delle attività estrattiva e metallurgiche* (Siena) – 1993, 532-560.

'Die späthallstatt- und latènezeitliche Eisenverarheitung in Radovesice', in J. Waldhauser u. A., *Die hallstatt- und latènezeitllche Siedlung mit Gräberfeld bei Radovesice in Böhmen II* (Gutachten, Praha) – 1993, 240-249.

'The Metallurgy of Iron: the Institute Research Programme', in in *25 Years of Archaeological Research in Bohemia* (Památky archeologické 85, Suppl. 1) – 1994, 287-291.

'Early Bloomeries in Central Europe', in *La sidérurgie ancienne de 1'Est de la France dans son contexte européen* (Besançon) – 1994, 181-188.

'Experimenting the Dalfsen furnace', in A. Boonstra (ed.), *IJzersterk: experimenten met ijzer winnen en smeden te Eindhoven* (Eindhoven: Stichting Prehistorisch Huis Eindhoven) – 1994, 32-37 (with M. van Nie, I. Joosten & P. Rijk).

'Early ironmaking in Europe', in A. Boonstra (ed.), *IJzersterk: experimenten met ijzer winnen en smeden te Eindhoven* (Eindhoven: Stichting Prehistorisch Huis Eindhoven) – 1994, 9-11.

– 1995

'The Development of Cutlery Technique in Medieval Bohemia', in P. Benoit & P. Fluzin (eds.), *Paléometallurgie du Fer et Cultures* (Belfort) – 1995, 537-539.

'Occasional smelting of iron in open bowl hearths in postmedieval Bohemian hammermills', in *La farga catalana en el marc de l'arqueología siderúrgica* (Barcelona) – 1995, 399-406.

'Reflections on Metallography of Early Iron Artefacts', in *Metallography* '95 (Košice) – 1995, 24-29.

'Small-Scale Rural Ironmaking in Migration Period Bohemia', in G. Magnusson (ed.), *Importance of Ironmaking: Technical Innovation and Change* (Stockholm) – 1995, 115-123.

'Výroba železa ve starokeltském světě', *Študijné zvesti AÚ SAV* 31 – 1995, 43-50.

'Das frühe Eisen: Von den Kleinwaagemengen zu der ersten Industrie', in *Ethnographisch-Archäologische Zeitschrift* 37 – 1996, 283-291.

'Metallographische Untersuchung des gestempelten römischen Eisenbarrens E 1170', in *Vitudurum 7. Beiträge zum römischen Oherwinterthur* (Zürich und Egg) – 1996, 195-196, 221-228.

'Vom Rennfeuer zum Hochofen. Die Entwicklung der Eisenverhüttung, 9.-14. Jahrhundert', in U. Lindgren (ed.), *Europäische Technik im Mittelalter* (Berlin) – 1996, 249-252.

'Les premières productions de ferro a l'Europe Central i Oriental', *Cota Zero-Revista arquelológia e ciéncia* 13 – 1997, 71-89.

'A Celtic bronze-coated iron sword blade from Manching', in *In Honour of G. Bachmann and R. Maddin* (Bochum: Anschnitt Beiheft 8) – 1998, 164-170.

'Celtic swords with 'striped' damask', in *Metallography* '98 (Košice) – 1998, 498-500.

– 2000

'Eine Eisenschüssel des sog. Schlesischen Typus aus Grube 95. Metallographische Untersuchung eines Messerbruchstücks dem Getreidesilo 126. Untersuchungen an drei Eisenmessern aus Grube 135 von Březno', in *Die altslawischen Dörfer von Březno bei Louny* (Praha: Archeologický ústav) – 2000, 143-147, 151-153, 160-165.

'Metalografie nožů z hradiště Doubravčice v Čechách. K vývoji nožířského řemesla na prahu středověku', in *Archeologie ve středních Čechách* 4/2 (Praha: Archeologický ústav) – 2000, 275-290 [sum. German] (with N. Profantová).

'The techniques of blacksmiths in Noricum and Central Europe', in *Il ferro nelle Alpi* (Bienno: Commune di Bienno) – 2000, 102-105.

'Notes on early Slav cutlery in Bohemia: Metallographic data', in *Metallography* '01 (Acta Metallurgica Slovaca 7) – 2001, 321-326.

'Special Committee: Ancient Siderurgy', *Prehistoria* 1 (1) – 2000, 2001, 199-202.

'Metalografický výzkum velkomoravské kroužkové zbroje z Břeclavi-Pohanska', *Sborník prací Filozofické fakulty Brněnské university Řada M - archeologicko-klasická* 51(7) – 2002, 77-81, 174-176 [sum. German].

'Metallographische Untersuchung des Schwertes aus Bešeňov' *Študijné zvesti Archeologického ústavu Slovenskej akadémie vied* 35 – 2002, 77-82.

'European iron blooms', in L. Nørbach (ed.), *Prehistoric and Medieval Direct Iron Smelting in Scandinavia and Europe. Aspects of Technology and Science* (Aarhus: Aarhus University Press) – 2003, 183-189.

'Metalografický rozbor středověkých železných nástrojů ze Sezimova Ústí', in J. Krajíc, *Sezimovo Ústí. Archeologie středověkého poddanského města. Praha* II (Praha: Archeologický ústav AV ČR Praha) – 2003, 173-194 [sum. German].

'Lingots et couteaux en fer d'Alésia: études archéométriques', *Revue archéologique de l'Est* 52 – 2004, 91-130. (with P. Fluzin, M. Mangin, E. Vega, P. Dillmann, M. Billon & E. Rabeisen).

'Problems with ancient smithing slag', in *Metallography 2004* (Acta Metallurgica Slovaca 10) – 2004, 664-667.

– 2005

'Hostivice-Palouky: Protohistorická výroba železa', in *Archeologie ve středních Čechách* 9(2) – 2005, 385-400 [sum. English].

'Metalografie železných nožů', in M. Kuna, N. Profantová et al., *Počátky*

raného středověku v Čechách (Praha: Archeologický ústav AV ČR Praha) – 2005. 259, 263, 355-356 [sum. English].

'Zasuté a obětované železo. Hromadné nálezy železz v rané Evropě', in *Z dějin hutnictví* 36 (Rozpravy NTM 204) – 2006, 3-12 [sum. English].

'Piece typu zagłębionego na terenie Europy w okresie wpływów rzymskich', in *50 lat badań nad starożytnym hutnictwem świętokrzyskim. Archeologia-Metalurgia-Edukacja* (Kielce: Kieleckie Towarzystwo Naukowe) – 2006, 137-149.

'Deutsch-tschechische Terminologie' *Německo-česká archaeologická terminologie* (Praha: Archeologický ústav AV ČR) – 2007. 335 p. (with A. Schebek, E. Čujanová & Z. Smetánka).

'Iron and Ironworking', in *The Archaeology of Medieval Europe. Eighth to Twelfth Centuries AD.* Vol. 1. (Aarhus: Aarhus University Press) – 2007, 220-223.

'Ulfberht, franský mečíř raného středověku', in *Z dějin hutnictví* 38 (Rozpravy NTM 207) – 2008, 17-20 [sum. English].

'Metallkundliche Untersuchungen von vier latènezeitlichen Eisengegenständen aus Berching-Pollanten', in A. Schäfer, *Die Kleinfunde der jüngerlatènezeitlichen iedlung von Berching-Pollanten, Lkr. Neumarkt i.d. Oberpfalz* (Rahden/Westf: Verlag Marie Leidorf) – 2010, 271-275.

References

Drašnarová, M. 1999, 'Bibliografie prof. PhDr. Radomíra Pleinera, DrSc. za léta 1989-1998', *Archeologické rozhledy* 51(2), 415-416.

Rataj, J. 1989, 'Bibliografie prací doc. PhDr. Radomíra Pleinera, DrSc.', *Archeologické rozhledy* 41(3), 314-321.

Richter, M. 1989, 'Životní jubileum R. Pleinera', *Archeologické rozhledy* 41(3), 312-314.

Richter, M. 1999, 'Jubileum . Pleinera', *Archeologické rozhledy* 51(2), 414.

ASEP Database (The Academy of Sciences of the Czech Republic - Publication Activity), viewed 7 June 2011, ⟨http://library.sk/i2/i2.entry.cls?ictx=cav&language=3⟩

Examples of research on ancient bloomery furnaces and the development of iron metallurgy in Europe

A new perspective on the ancient bloomery smelting furnace with a pit
by K. Bielenin

The canal-pit and its role in the bloomery process: the example of the Przeworsk culture furnaces in the Polish territories
by S. Orzechowski

The oldest iron smelting furnaces in Denmark
by A. Jouttijärvi and O. Voss

Some results and questions of archaeometallurgy in Hungary
by J. Gömöri

Some aspects of the development of Great Moravian iron metallurgy
by V. Souchopová and J. Merta

Norway as a bloomery iron producer
by A. Espelund

A new perspective on the ancient slag-pit bloomery smelting furnace

K. Bielenin

The ancient slag-pit smelting furnace is a fundamental component of the metallurgical technology used in the ancient Europe outside the boundaries of the Roman Empire. The main element of this furnace, which survived for many centuries and is the basic source of research, is the slag block – a waste product which settled in the lower part of the furnace, known as the slag pit.

Using this furnace the smelter made an important advance which had a great impact on the following centuries. This consisted in transferring slag from the reduction zone of the furnace into the specially prepared pit (Fig. 3: a, b, c). As a result the ancient master could separate slag from the iron bloom as it collected and obtain a piece of iron ready to be forged.

The highlighted elements on the surface of the slag block include the elements subject to unimpeded solidification (Fig. 4). These elements provide evidence of the metallic iron zone, free of slag, in this furnace. Furthermore, the resulting product was not a conglomerate of slag and iron, as was the case of the experimental research, but a deslagged iron bloom typical of a furnace from which the slag is tapped. The iron bloom from the bloomery furnace did not require the so called post-reduction stage as it has been assumed so far.

The results presented here, which stem from the analysis of the surface of the unimpeded solidification on the slag block, and a new perspective on the bloomery furnace, are currently subject to verification and metallurgical research at the AGH University of Science and Technology in Kraków.

Smelting furnace - Slag-pit bloomery furnace - Bloomery process

Introduction

The ancient slag-pit bloomery shaft furnace and the metallurgical process involved were first studied at the beginning of the 1950s by Zespół Historii Polskiej Techniki Hutniczej [the Study Team for the History of Polish Metallurgical Technology] under the leadership of Professor Mieczysław

Radwan. Professor Radwan undertook the research by actively participating in the study of ancient iron metallurgy in the Świętokrzyskie Mountains conducted by the Archaeological Museum in Kraków (Bielenin & Radwan 1959). In 1959 after studying the archaeological sources Professor Radwan began experimental research into the reconstruction of the furnace, the metallurgical process itself, and the character of the resulting iron.

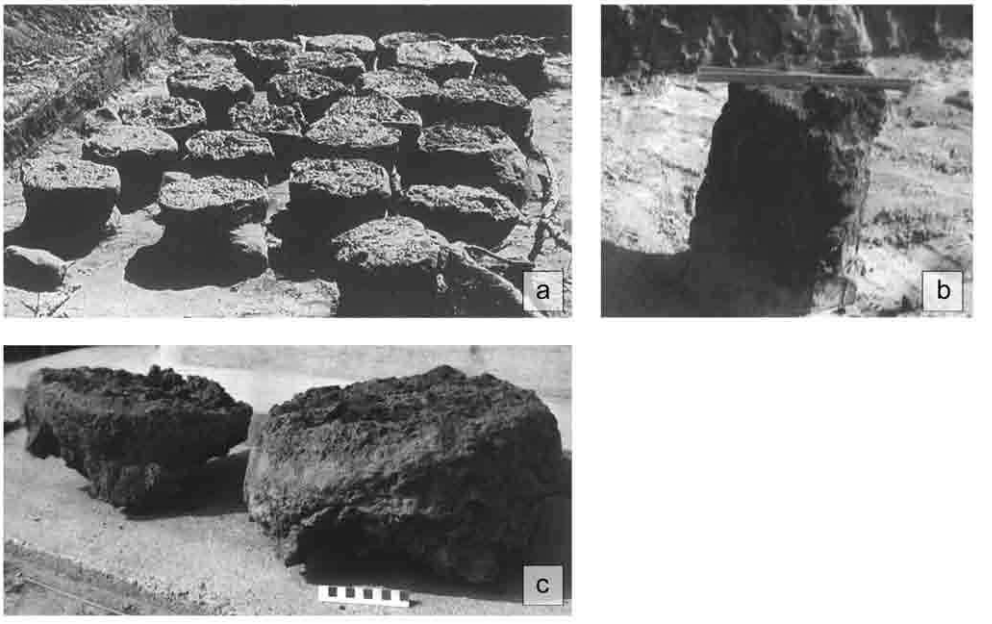

Figure 3: a: Rudki (Świętokrzyskie Mountains). The smelting workshop of the bloomery furnaces of the pit type. The pits filled with slag blocks which were not destroyed during fieldwork. The preserved upper parts with the surface of the unimpeded solidification. The weight of blocks approx. 100kg. b: Gardzienice (Świętokrzyskie Mountains). The smallest bloomery furnace Kunów 1. The weight of the block approx. 8kg. c: Langental (Burgenland, Austria). Two slag blocks. The weight of the block approx. 40kg. 1969. All photographs by K. Bielenin.

After of a series of 31 experiments, which were later conducted together with Dr Radomír Pleiner from the Czechoslovakian Academy of Sciences in Prague, Professor Radwan became aware that the metallurgical issues involved were much more complex than he and others had anticipated (Radwan 1933, 1937). He announced this in his work published in 1965 where he mentioned that "one may say that the experiments confirmed the high abilities of the ancient smelters. They were able to obtain great results during the smelting process, which is indeed extremely complex. The reduction and oxidation phenomena intermingled in this process while carburization and decarburization proceeded. As a result it was easy for

the iron bloom to burn" (Radwan 1956, 240).

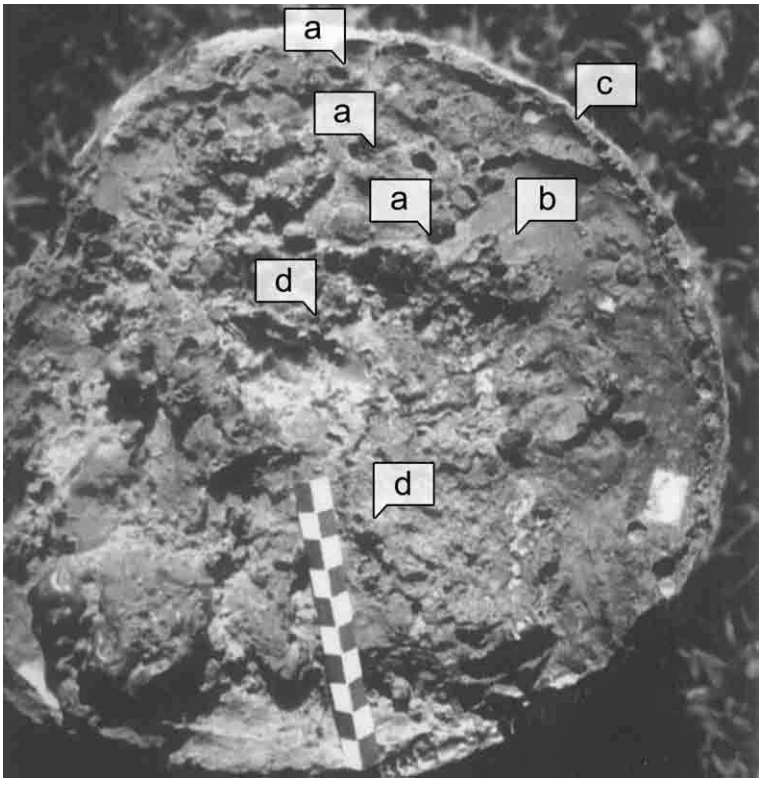

Figure 4: Kowalkowice (Świętokrzyskie Mountains). The upper part of the slag block with the characteristic surface of solidification: a: traces of the bursting gas bubbles; b: the surface wrinkle; c: casting shrinkage at the edge; d: elements of the clay and a larger piece of the wall of the shaft removed after the smelt. Photograph by K. Bielenin.

Professor Radwan became aware that practical knowledge was missing that enabled the ancient smelter to separate the liquid slag from the particles of iron subject to reduction. It is a phenomenon which is manifested by the slag blocks (Fig. 3, Fig. 4, Fig. 6 /Plate III/) where the amount of the microscopic pieces of iron does not exceed 1% (Holewiński 1965; Neuman 1954).

Unfortunately his sudden death prevented Professor Radwan from continuing the experiments. Further research was carried out by Professor Różański. Despite the changes in the parameters as far as the height of the shaft and the blowing rate are concerned, the research produced similar results – a spongy conglomerate of small pieces of metallic iron mixed with slag and charcoal.

During experimental research conducted both in Poland and other countries a similar conglomerate of iron and slag was obtained (Fig. 5). It additionally contained charcoal, which gathered slightly below the air

Figure 5: Conglomerate of iron and slag, the result of the experimental smelt in Nowa Słupia (Świętokrzyskie Mountains, 1964). Photograph by K. Bielenin.

blast intake. It proved impossible to tap all the slag to the pit and obtain a structure of unimpeded solidification on its surface (Bielenin 2002). As a result the European teams conducting similar research somewhat incredulously entertained the idea that the ancient smelter using the bloomery furnace would obtain such a form of iron.

For the next fifty years the experimental research directed the analysis of the process towards the next stage, the so-called post-reduction stage. Although the pit and the slag block with the surface of unimpeded solidification indicated the correct experimental direction, they were ignored. It should be emphasized that these sources were widely available to the researchers carrying out experiments in this field.

This second stage was used with other types of furnaces in other cultural surroundings. The author of this paper was in agreement with Professor Radwan on this point from the very beginning and presented such a view in the second edition of Starożytne Hutnictwo Świętokrzyskie [Ancient Metallurgy in the Świętokrzyskie Mountains] (Bielenin 1992, 82). Study of the slag block suggested, however, that it conceals the abilities of separating slag from the reduced iron bloom (ibid., 58, fig. 26). Change in this position only became possible when the upper part of the slag block was

closely observed and analysed (Bielenin 1998–1999).

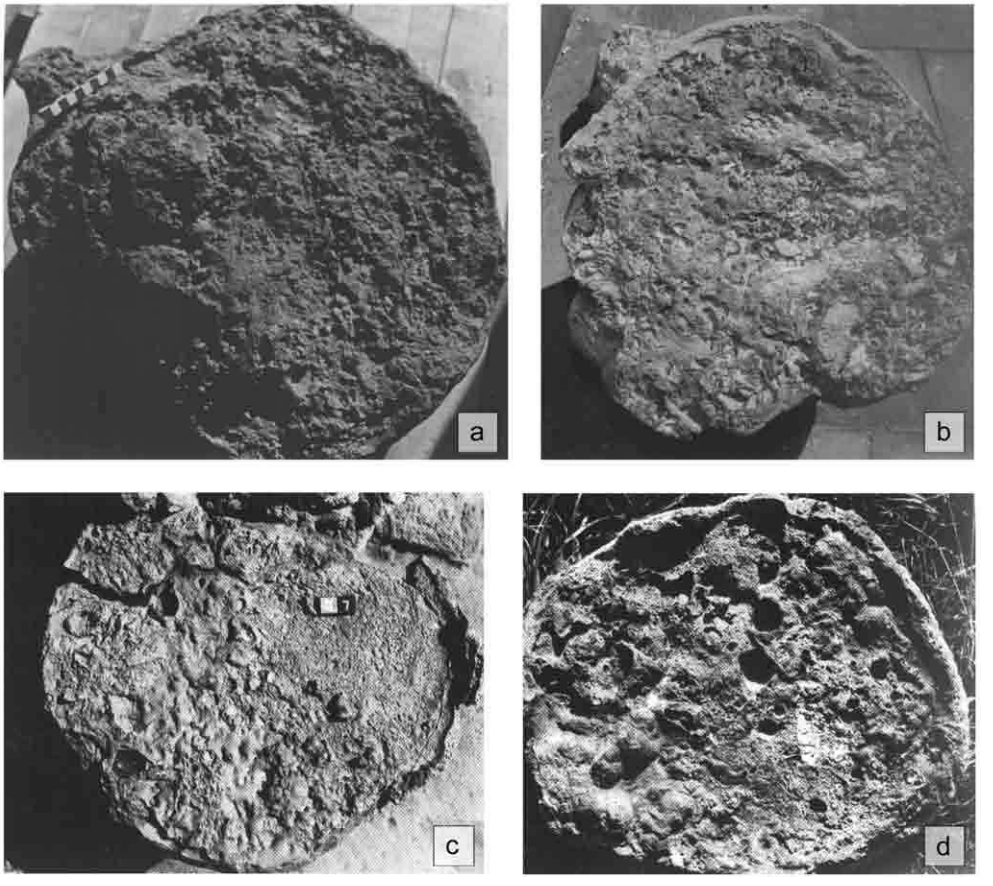

Figure 6: Examples of different appearances of the surface of the unimpeded slag solidification (average block diameter approx. 45cm, weight 80–100kg: a: Wronów (Świętokrzyskie Mountains), photograph by K. Bielenin; b: Rudki (Świętokrzyskie Mountain), photograph by R. Łapanowski; c: Brwinów (Masovia); d: Młochów (Masovia). Photographs by S. Woyda.

At the beginning of 2002 experimental research into the reduction process in the ancient bloomery furnace was again undertaken by AGH metallurgists in Kraków – Professor Mirosław Karbowniczek and Dr Ireneusz Suliga from the Faculty of Metals Engineering and Industrial Computer Science.

The research focused on the slag blocks that filled the pit of the furnace. The scientific research was intensified in 2002. As a result of the earlier archaeological observations of the slag blocks from the Świętokrzyskie Mountains and other sites, both in Poland and in other countries, it became possible to distinguish and characterize the surface of the unimpeded solidification that is present on the upper part of the slag block (Bielenin

2002). The distinguishing elements of this structure are (Fig. 4 /Plate III/):

- an usually equal level of the slag block that fills the pit
- solidified traces of bursting gas bubbles of different sizes on the surface
- a surface wrinkle that is sometimes visible
- a vertical side edge: casting shrinkage at the edge shows that the pit was filled with hot slag, the level of which decreased when it solidified
- fragments of the clay walls of the shaft that can be found in the solidified surface of slag. The walls were taken to pieces immediately after the casting had been finished (Bielenin 1998–1999).

There are certain groups of features that can be defined with reference to the surface of the unimpeded solidification of slag. These features are the elements of direct reduction technology of the bloomery furnace (Fig. 3, Fig. 4, Fig. 6 /Plate III/):

1. The surface of the slag block with the bursting gas bubbles and the casting shrinkage at the edges indicate the degree of the liquidity of the slag. These factors allowed an unconstrained settling of slag in the pit and filling up the pit all the way to its upper edge. They also show that the amount of charge was calculated by the smelter so that the slag level in the pit would not overrun the upper edge of the pit.
2. Slag settling in the pit seems to be a feature and a one-off process which ended the smelting process. The earlier research into the slag block shows that "pure" slag (containing less than 1% of the reduced metal) settled in the pit (Holewiński 1956; Neuman 1934). Slag did not mix with the pieces of the solidified metal from the iron bloom.
3. The pit was filled with inflammable materials (brushwood, wood, straw, etc.)
4. The hearth of the furnace was located in the shaft below the air intakes
5. Slow burning of the pit filling below the iron bloom resulted in increasing the space necessary for the slag to flow through the pores of the iron bloom. Slag eventually broke down the filling and settled in the pit. This was a signal for the smelter to dismantle the shaft in order to remove the iron bloom and finish the process.
6. A characteristic surface of unimpeded solidification with its characteristic features was formed on the surface of the slag

Taking into consideration the settling of the entire amount of slag in the pit and the lack of contact between the surface of the slag and the iron bloom, the conclusion may be drawn that the iron bloom and the entire zone of metal subject to reduction were optimally deslagged in this furnace. It furthermore shows that the product of the ancient smelter was not a conglomerate of slag and iron, a product which has caused many problems to modern researchers.

The conclusions drawn from analysing the surface of the unimpeded solidification makes it possible to bring to light that troublesome episode, the so-called post-production stage. In this case the iron bloom did not require such a stage, and neither did the iron blooms from the furnaces in which the slag was tapped. After the iron bloom was taken out of the furnace it was subject to skilful forging aimed at condensing the inner structure, forming it, and dividing into pieces of arbitrary size and shape.

Metal science research

The earlier metallurgical science research results concerning the slag block were focused on the segregation of elements and phases on the cross-section of the slag block as well as on the degree of the liquidity of slag. These results suggested that the forming of the block in the pit proceeded by means of crystallization of the liquid slag that filled the pit and not by the slag flowing continuously throughout the smelting process (Suliga 2006, 267–72). Further evidence was found during the study of the slag blocks: it consists in the secondary reduction that would have resulted from liquid slag settling in the pit after it had been in contact with charcoal (Suliga & Kargul 2007, 621).

The verification of the process by metallurgical science shows clearly that the smelter obtained an iron bloom ready for forging which had been optimally deslagged (Bielenin 2002, 2005; Suliga 2006; Suliga & Kargul 2007; Bielenin & Suliga 2008).

The prevalence of the bloomery furnace across the vast territories of Central and Northern Europe and the existence of many development stages of the furnace indicates a shared understanding and employment of the technology and the creativity that led to metallurgical innovations at that time.

The conglomerate of iron and slag obtained during research was probably also a product of the ancient smelting process in the initial stages of the development of metallurgy. In all probability, after many failed attempts and much effort, our ancient master found a solution to this problem. This consisted of preparing a pit beneath the hearth where liquid slag

could settle. This is the most probable genesis of the bloomery furnace of the pit type as envisaged by the ancient smelter or smelters, who would prepare a pit that would function as a container for slag. The slag block with its surface of solidification proves that the pit served to deslag the molten metal completely (Fig. 3, Fig. 6 /Plate III/).

The analysis of the surface of the unimpeded solidification shows that the ancient smelters obtained a fully deslagged iron bloom not by means of complex operations of the so-called post-production stage but thanks to the pit, which functioned as a container for slag.

Conclusions

The first person to confirm the considerable abilities of the ancient smelter was the Professor Mieczysław Radwan in 1965. This recognition, however, was not a breakthrough in the experimental research. The researchers at the time were satisfied with production of the conglomerate of iron and slag, a discovery of the time. Further efforts were directed at treating the conglomerate. Forty years had to pass for a new archaeological perspective on this issue to present itself. This perspective was formed on the basis of a detailed analysis of the archaeological realities such as the pit and the slag block.

The verification of this new archaeological conception conducted by the AGH metallurgists in Kraków confirmed and supplemented it with data concerning the deslagged iron bloom, thus supporting Professor Radwan's high opinion of the smelter's abilities (Suliga 2006; Suliga & Kargul 2007).

Deslagged malleable iron was being obtained in bloomery furnaces at the time of the La Tène culture. The practice, which was known throughout Europe during the period of Roman influence, is a great achievement even from a modern perspective. This great invention was the proverbial milestone, the first technological revolution in metallurgical development (Bielenin 2002). Today it seems to be forgotten and so does its waste product, the slag block.

How did the ancient master achieve these results? This basic question is a separate topic for further series of experimental research. Currently it seems necessary to create a new research scheme which would include the conclusions drawn from the features of the pit and the slag block. The surface of the unimpeded solidification, see Fig. 7, is a tangible record of the final stage of the ancient smelting process, a record which has not been taken into consideration so far.

Figure 7: Piece of an intact smelting workshop and the preserved slag blocks from a large smelting centre (Wolkenberg 30). Photograph by I. Spazier, Arbeitsberichte zur Bodendenklamlpflege in Brandenburg, 3, 1998, 97–103.

References

Bielenin K. & Suliga, I. 2008, 'The ancient slag-pit furnace and the reduction process in the light of a new archeological concept and metallurgical research', *Metallurgy and Foundry Engineering* 34(1), 53-78.

Bielenin, K. 1973, 'Dymarski piec szybowy zagłębiony (typu kotlinkowego) w Europie starożytnej', *Materiały Archeologiczne* 14, 5–101.

Bielenin, K. 1974, *Starożytne górnictwo i hutnictwo żelaza w Górach Świętokrzyskich*, (Kielce). 1992, second edition.

Bielenin, K. 1998-1999, 'Einige Bemerkungen zu den Rennofenschlacken der Schlackengrubenöfen', Internationales Symposion Linz-Freinberg 1998, *Archeologia Austriaca* 82-83, 523-528.

Bielenin, K. 2002, '*Kilka dalszych uwag dotyczących starożytnego hutnictwa świętokrzyskiego*', in S. Orzechowski (ed.), *Hutnictwo świętokrzyskie oraz inne centra i ośrodki starożytnej metalurgii żelaza na ziemiach polskich* (Kielce), 11-25.

Bielenin, K. 2005, 'Kloc żużla dymarskiego z Boleszyna. Uwagi o znaczeniu badań powierzchni kloców żużla dymarskiego', *Materiały Archeologiczne* 35, 189-198.

Bielenin, K. & Radwan, M. 1959, 'Badania nad starożytnym hutnictwem

żelaza w regionie Gór Świętokrzyskich w latach 1956 i 1957', *Materiały Archeologiczne* T. I, 279-323.

Holewiński, S. 1956, 'Wstępne badania starożytnych żużli skupionych na niektórych terenach Polskich', *Archiwum Hutnictwa* I z. 2, 251-282.

Neumann, B. 1951,'Die älteste Verfahren der Erzeugung technischen Eisens', *Freiberger Forschungshefte* t. 6 (Berlin).

Radwan, M. 1933. 'Pierwotne hutnictwo żelaza na północnym zboczu Łysogór', *Ziemia* 26 (2-3), 73-77.

Radwan, M. 1937, 'Z dziejów wytopu', *Hutnik* 6, 320-327.

Radwan, M. 1965. KHNiT; 10, 1956, 239-240.

Suliga, I. & Kargul, T. 2007, 'Efekt redukcji wtórnej w starożytnych żużlach dymarskich', *Hutnik* 11, 616-622.

Suliga, I. 2006, 'Próba metalurgicznej weryfikacji koncepcji archeologicznej K. Bielenina „powierzchni swobodnego krzepnięcia" starożytnych kloców żużlowych, na podstawie kloca z Kowalkowic, gm. Waśniów', *Materiały Archeologiczne* 36, 267-272.

The canal-pit and its role in the bloomery process: the example of the Przeworsk culture furnaces in the Polish territories

S. Orzechowski

Some bloomery slag-pit furnaces in the Przeworsk culture area exhibit various types of side canal connecting the ground surface with the pit. These are the remains of devices to support the blowing system of the bloomery furnace, located in its shaft part. Several types of these devices were identified, ranging from a simple widening of the side of the pit to regular bow-shaped canals. The devices were not widely used, though in some regions (particularly Mazovia) 10–15% of the furnaces were equipped with them at various times. It has been assumed that such canals facilitated drying the pit and enhanced the draft only at the initial stage of the smelting process. However, numerous bloomery furnaces from Mazovia and the Świętokrzyskie Mountains region indicate that their role did not end at that stage and that they could have facilitated operation of the furnace during the whole smelting process.

Archaeology - Ancient metallurgy - Przeworsk culture - Slag-pit furnace - Canal-pit - Bloomery process

Introduction

Slag-pit furnaces used by the peoples inhabiting the central and northern Europe at the end of antiquity played a role that is impossible to overestimate in the history of those regions (Bielenin 1973, 1992; Pleiner 2000, 45–47, 149–63; 2006). This unique technological and cultural phenomenon constituted the basis for iron production for over half a millennium, in many regions showing astonishing stability of form and the solutions applied. Huge metal-producing centres which, during that period, existed in the Polish territories within one of the greatest and longest-lasting cultural creations of barbarian Europe, known in archaeology as the Przeworsk culture, were based almost solely on that type of furnace (Orzechowski, 2007a).

The slag-pit furnace still remains a mystery for science and poses serious problems in the correct reconstruction of the smelting process involved.

Smelting experiments have not yet answered the vital question of how the iron sponge could be separated from the slag forming in the pit. The conglomerate containing a mixture of slag and iron, obtained by contemporary scientists, in no way resembles the well liquefied ancient slag blocks with the distinctly marked surface of solidification (Bielenin 2002, 14–17; 2005, 189–90).

The air-inlet system was one of the factors that played a crucial role in the process. It is one of the most difficult issues connected with this problem, and its reconstruction remains controversial in many regions. The air-inlet openings were located in the above-ground part of the furnace which was demolished each time during the dismantling the shaft. It is assumed that the basic ventilation system was supported by the so-called canal-pits, which accompanied some bloomery furnaces and constituted an important construction element of a significant number of pits, at least during the earlier phase of metallurgical development in this area. Discovering their function and the role they played in the smelting could become a key factor for the understanding of the operating principles of such furnaces. They have been mentioned several times in literature, but they have never been studied separately (Bielenin 1973, 56; 1983, 55–6; 1992, 72-73; Woyda 1977, 480–81; 2002, 131–36; Orzechowski 2007, 206–09). It is for this reason that a presentation of those very interesting devices found in the Przeworsk culture sites and an attempt to identify their function and significance for the correct reconstruction of the bloomery process are the objectives of this study.

What is a canal-pit?

A wide variety of shapes and sizes of the devices being considered makes it somewhat difficult to define them unambiguously. The term 'canal-pit' does not fully reflect the character of all its variations encountered so far: these include both shallow open pits and niches made in the pit walls, as well as enclosed pipe-like underground canals leading into the pit. To be recognized as canal-pits they had to fulfil the basic condition, namely that they should link the pit with the ground surface outside the external perimeter of the furnace shaft. In older literature, the term dowierzchniowy ('up-leading') which, though grammatically incorrect, best reflects the character of such a structure (Bielenin 1973, 56; 1992, 78). In conformity with what has been written earlier, the term 'canal-pit' will be applied in this paper to openings associated with the pit that were intentionally drilled in the ground in the form of various niches or side extensions of the pit, as well as the proper enclosed canals that linked the lower

part of the furnace with the ground surface on the outside of the shaft. Such type of devices has been rarely registered in the areas inhabited by the Przeworsk culture people. In Silesia, where a particularly vast variety of forms and sizes of bloomery furnaces occurred, they (canal pits) were found only in few sites. Only in Tarchalice one could be sure that some of the furnaces were equipped with such devices (Domański 1972, 427-28, ryc. 24, 431). P. Weiershausen (1939, 109) mentions an indefinite canal in reference to the bloomery furnaces in Sośnica. We are not certain either, whether the single slag outflows outside the pit range found in the site in Lizawice could have indicated the presence of the canals in question. Their presence has been detected in only some tens of furnaces in the Świętokrzyskie Mountains region, and it was only in Mazovia that they appear to have been more frequently used. It must be noted, however, that the actual number of furnaces equipped with such devices is very difficult to determine, and in many cases their apparent absence could have resulted from the poor state of preservation of the discovered structures. If the upper parts of the furnace were destroyed, such types of device had little chance of surviving. The ones that were preserved were generally those that slag had flowed into, leaving them permanently fused with the block forming in the pit. It has to be noted, however, that even though some of the destroyed structures might have possessed them, the significant majority of the furnaces discovered in the Polish territories does not indicate the presence of any such type of device. Outside the Przeworsk culture area only a few are known from sites in Germany, such as Isernbarg (Hayen 1968),or the Czech Republic, such as Buštěhrad and Ratenice (Pleiner 1958, 34).

Types of canal-pit

It has already been stressed that canal-pits were most frequently used in Mazovia, where they occurred in a variety of forms encountered nowhere else Fig. 8 /Plate IV/). The available data indicate that up to 70% of older pits and several percent of the more recent ones were equipped with various extensions or canals of varying shape, size, and direction (Woyda 2005,149). These data may not reflect the actual number of structures equipped with the devices in question. This group most probably encompasses all the structures whose pits possessed walls extended in the shape of irregular niches, although with no outlet outside the furnace. According to the above definition, canal-pits may have occurred in 10–25% of the furnaces, depending on chronology (Woyda 1977, 480–81). Among the five types of pit (types I–V) defined by S. Woyda, as many as four were

equipped with various forms of canal-pit (types II–IV) (Fig. 9):

Type II: The pit with a one-sided widening running along the whole height of its core in the form of a canal on the plane of a circle, the outlet of which was located very close to the shaft. Slag filled it in a continuous way, simultaneously with the pit proper.

Type III: The pit with an adjacent shallow hole which was connected to the upper part of the pit through a horizontal canal. Slag flowed into it only at the final stage of filling the pit.

Type IV: The pit with a regular vertical canal which reached the core of the pit at the bottom. The canal was flooded with slag from the top through a horizontal connecting inlet, which is not always preserved.

Type V: The pit with a diagonally inserted canal joining its core above the bottom level. Slag flowed in from the top through a horizontal canal.

The canal-pits discovered in Mazovia so far were made on the plane of a circle, and their size, depending on the type, varied in diameter from 10cm to 27cm, with the pit diameter between 35cm and 50cm. The mass of slag found in the canal frequently constituted a significant percentage of the volume of the material filling in the pit proper, which gave the impression of there being double pits there (Fig. 8: 1 /Plate IV/). Unfortunately, there are no detailed statistics available that would allow us to identify which of the types described by S. Woyda occurred most frequently there.

All the types of canal mentioned were flooded with slag directly connected to the block and, moreover, the slag was generally on the same level as or lower than the upper surface of the block. There were, however, cases where the cast of the canal was located above the block (Type V). The character of that slag is also worth noticing, since in its upper parts it is generally composed of a highly liquefied mass with a layered structure. In some cases as many as 15–20 thin layers, measuring between 0.5cm and 2cm, could be counted Fig. 10). Between the inflows of individual amounts of slag there must have been intervals that allowed them to solidify. This can be confirmed by the presence of dust and sand on the surface of each of them (Woyda 2005, 135). Macroscopic analysis of the structure of slag forming in the furnace equipped with a canal-pit when compared with that from furnaces without this element showed no distinct differences in its character. It is worth noticing, however, that no slag with a porous structure and imprints of charcoal or swellings in the shape of vertical icicles, so characteristic for standard pit furnaces, were found among the slag casts of canal-pits.

The three main types of canal-pits for the furnaces in the Świętokrzyskie Mountains region were identified by K. Bielenin (1992, 72-73), (Fig. 11):

Type A: Very carefully moulded, arched rounded canals joining the pit slightly above the bottom level. Its outlet was located at a distance from the external wall of the shaft. Such canals could have been partially flooded with slag, but there are also known specimens which show that the canals remained unobstructed till the very end of the process.

Type B: An arched canal on the plane of a quadrangle, cutting into the side wall of the pit and reaching the bottom part. Its outlet was located directly at the base of the shaft. It was filled with slag in a continuously way, simultaneously with the pit proper.

Type C: A canal cutting into the side wall of the pit at a right-

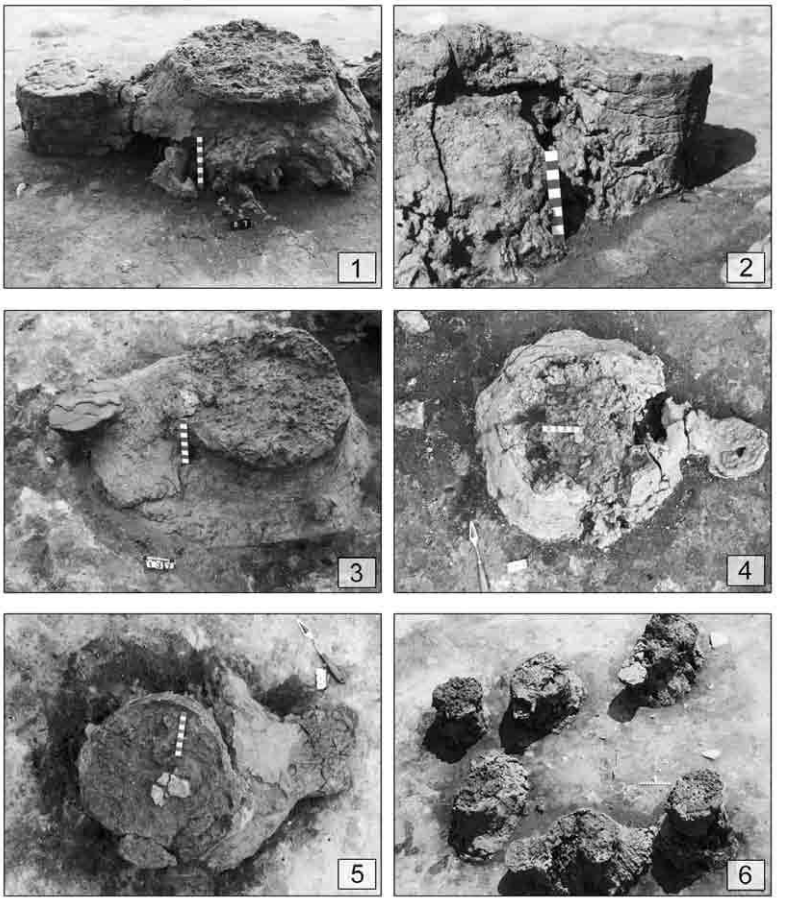

Figure 8: Selected examples of furnaces with canal-pits from Mazovia, Brwinów (1-6). Photograph by S. Woyda.

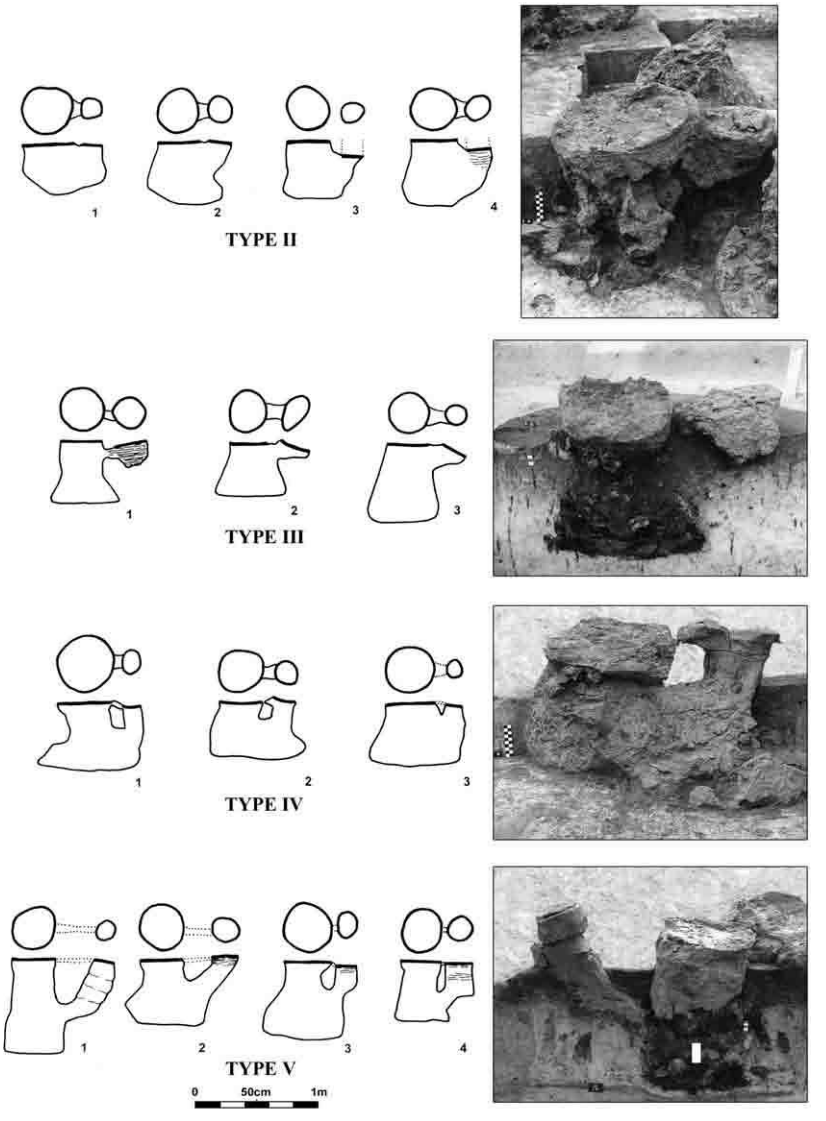

Figure 9: Various types of pit in bloomery furnaces equipped with canal-pits from the Mazovia area, according to S. Woyda (2002, 132–33, Fig. 15).

angle, the outlet of which was located immediately in the furnace wall. Slag flowed into it simultaneously with the main pit forming a kind of vertical thickening of the block.

In addition to this classification, there were some hardly visible traces of devices which might have served similar purposes and the presence of which was confirmed by traces of more strongly burnt out soil on the walls of the pit. It appears that making various kinds of small niche or attempts to supply air into the pit by cutting holes in the wall from the

Figure 10: Brwinów, Dis. Brwinów. A sample of canal-pit with clearly marked layers of slag. Photograph by S. Woyda (2002, 137, Fig. 18).

outside during the process, were made in order to clear it temporarily. That facilitated complete burning out of charcoal and better liquefying of slag.

The shape and size of canals accompanying the furnaces in the Świętokrzyskie Mountains region were also quite varied. Carefully hollowed out in loess, arched canals of type A measured about 6–12cm in diameter, with their round outlets located up to 20cm from the outer edge of the shaft base. Type B was generally rectangular in cross-section and measured 8cm by 14cm, whilst Type C was semi-circular, about 6cm in diameter (Bielenin 1973, 56).

It has already been emphasized that the canal-pit was not commonly used in the Świętokrzyskie Mountains area. Its traces have been found only in seven out of 117 excavated sites so far. Five more blocks showing traces of such canals are known from surface finds. Only 52 furnaces equipped with that interesting construction element have been registered so far, and in 36 cases they represented Type A. (Baszowice, Kunów, site 3, Łomno, site 23, Mirogonowice, site 1, Pokrzywnica, site 1, Skały, site 2, Worowice, site 1, Wronów, site 1). Furnaces with Type B and C canals occurred *in situ* in twenty structures (Marcinków, site 1, Podchełmie, site 1, Pokrzywnica, site 1, Skały, site 2); others were simply unstratified finds (Orzechowski 2007b, 206–7, Tab.15). In several cases differentiating between the latter two types was impossible because of the damage to the blocks and so they are considered jointly in the general summary.

The chronological aspect of the occurrence of canal-pits in smelting sites of the Przeworsk culture is also worth noticing. In Mazovia it was

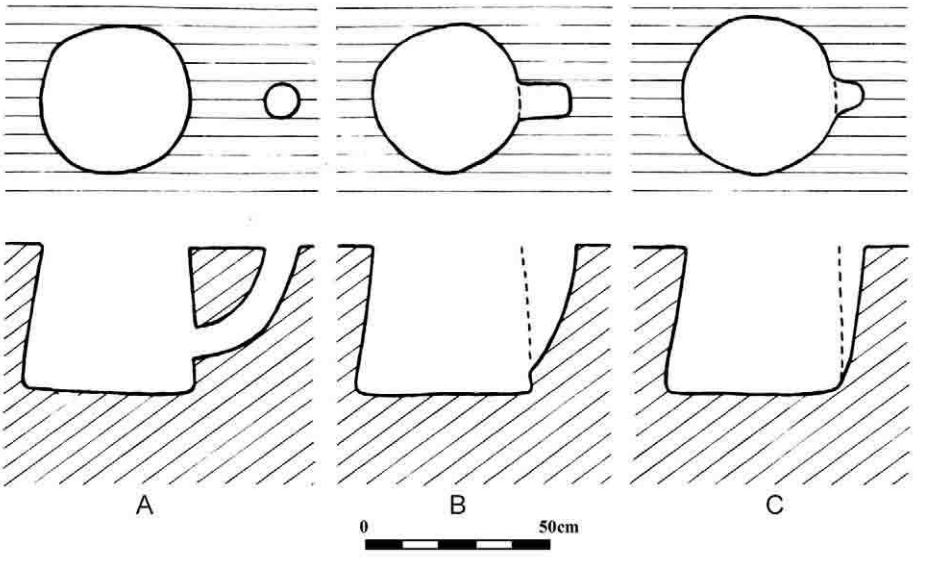

Figure 11: Diagrams of various types of canal-pits in the Świętokrzyskie Mountains (K. Bielenin (1992, 73, Fig. 34)).

possible to observe a distinct tendency towards reducing the number of such devices with the passing of time.

A similar situation could also be observed in the Świętokrzyskie Mountains, where such devices occurred almost only in unorganized slag-pit clusters, which represent mostly an older phase of development. In the literature only one organized slag-pit cluster site (Łomno, site 23), representing the type of two rows of four furnaces (2×4), has been mentioned so far, where a canal-pit was registered (furnace 45). It is possible, however, that some of the blocks classified as unstratified could have come from large slag-pit furnace clusters of that type. More recent research provided information about the more frequent occurrence of the devices in question in organized slag-pit furnace clusters as well. Slag-pit furnace cluster 3 (Type 3×3) in Pokrzywnica, site 1, can serve as an example, where among the group of 140 furnaces ten structures were registered that had been equipped with canal-pits of various kinds (Orzechowski 2006, 45). In slag-pit furnace cluster 8 (Type 2×3) at least one such canal was found. One must assume that in reality such devices occurred in many more furnaces, particularly those in which canals were in the form of a small side extension of the pit (Type B and C), and so were more likely to be destroyed. In the case of furnaces of which only the bottom part was left, these are practically undetectable. However, it must be emphasized that in large organized slag-pit clusters representing the heyday of activity of the Świętokrzyskie Mountains metallurgical centre, canal-pits occur

extremely rarely.

The function of canal-pits and their significance for the reduction process in pit furnaces

Opinions concerning the function of canal-pits are fairly unanimous, although there are also some differences of opinion among the scientists. According to K. Bielenin (1973, 56; 1992, 72), the canal-pit was operating while drying and heating the furnace and during the first stage of the smelting process. Later, its role gradually came to a close as it became filled with slag flowing into the pit. Although basically correct, this view does not take into consideration all the variations of this device that have been observed so far, particularly those in the furnaces in Mazovia. The issue seems also to be far more complex in the case of the Type A canals from the Świętokrzyskie Mountains. The furnaces recently discovered in Pokrzywnica, Dis. Pawlów, were equipped with perfectly preserved canals of that type (Nos. 1, 13, and 14) which permits the assumption to be made that their role was not restricted only to the initial stages of the smelting process. These structures had regular, arched canals measuring 15cm in diameter, of which 40cm long fragments were preserved, and reaching the bottom of the furnace pit (Fig. 12: 1-2 /Plate V/). Slag was not found in any of them, which proves that they remained unobstructed until the end of the smelting process.

A similar view concerning the role of canal-pits which could support the main air-inlet system (even up to the end of the smelting process) is represented by S. Woyda (2002, 35) with reference to metallurgy in Mazovia. Based on observing the extremely varied forms of canals in Mazovia and their occurrence in large numbers in smelting sites there, he claims that they not only supported the proper air-inlet system but at some periods they took over its leading role. According to that scientist, the niches and canals in question could have served to pump air into the pit, using bellows fitted with organic tips, which would explain their absence from archaeological material. Thanks to that the temperature in the pit could have been maintained, which facilitated the inflow of slag, or even the reduction zone could have been oxygenated from the bottom (Woyda 2005, 153). In explaining their operating principles, this author has recently presented a diagram showing a possible method of the slag inflow into the canals and of air circulation there (Woyda 2005, 154), (Fig. 13). It is very difficult to refer to the suggested solutions, although the general principle seems to be right. The solutions are based on real life and not only model specimens of various pits equipped with these canals. The issue requires further more

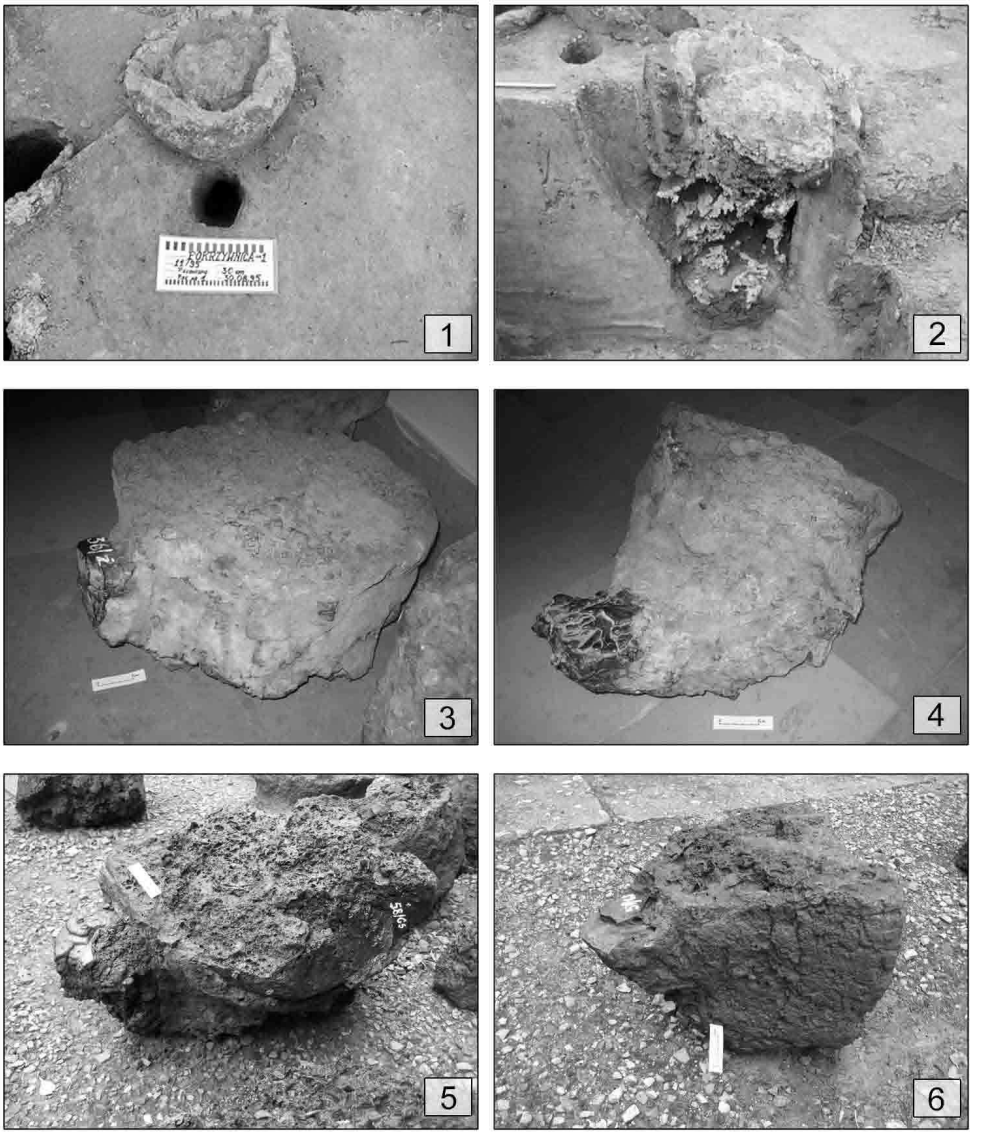

Figure 12: Selected samples of furnaces with canal-pits from the Świetokrzyskie Mountains: Pokrzywnica (1-2), Skarżysko-Kamienna (4), Tarczek (3), and Garbacz Skała (5-6) sites. Photographs by S. Orzechowski.

detailed research with the use of new methods of exploration of such objects, particularly with regard to the detection of horizontal canals which, according to the author quoted above, joined the upper part of the pit with the canal outlet (Tomczak 2007, 181–82).

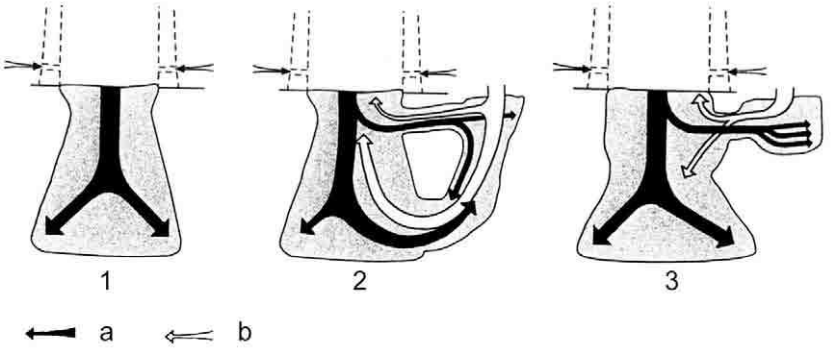

Figure 13: Diagram showing air inflow (white arrow) and slag inflow (black arrow) in the pit and its accompanying canal, according to S. Woyda (2005, 154, Fig. 19).

General conclusions

The presence of canals connecting the bottom part of the furnace with the surface that have such varied and frequently complicated forms indicates that the pit was not, as it had generally been thought to be, the passive part of the furnace, its role limited solely to storing the slag formed during the smelting process. Because of the canals, which ensured that it remained unobstructed, it could influence the various stages of the process (Woyda 2002, 135; Orzechowski 2007b, 208).

The frequently complicated form and the care with which they were constructed indicate that the canals were made immediately after the pit had been dug out, and certainly before the shaft was built. This in turn shows that the devices constituted an important structural element of the furnace, one which was carefully planned and which had a significant role in the smelting process. The view that they might have been made while the smelting process was in progress cannot be sustained. It is only possible to talk about canals being made during the smelting process if there was an emergency attempt to perforate the pit walls in order to supply air temporarily to the pit.

The idea of using a canal-pit is an obvious example of seeking new technological solutions aiming at facilitating the smelting process. They ensured better ventilation of the furnace by supplying the air not only to the pit, but through it also to the lower part of the shaft. This resulted in the slag being well liquefied and so easier to drain off from the reduction zone leaving the forming iron sponge. It is possible to make this claim on the basis of observation of slag blocks which are much better liquefied on the side of canal-pits. It is also confirmed by experimental research. It was found out that allowing air draft into the pit had a beneficial effect on

the process of liquefying slag. If the results of the recent research, which indicate that solidification of the block was continuous for all the volume of slag filling in the pit, thereby suggesting a single inflow of slag into the pit (Suliga 2006, 268), are confirmed, it would mean the canal-pit could have played a significant role at this stage of the smelting process.

Canal-pits could also have served another additional purpose. The traces of an interrupted inflow of small amounts of slag, mentioned before, could have provided the smelter with important information about the process itself. Having no direct insight either into the reduction zone or into the pit, by occasionally letting out some slag into the canal the smelter could have deduced the course of the process from the slag properties.

It must finally be noted that canal-pits are associated more with an early stage of productive activity and were used less frequently as time passed. This regularity seems to lead to a surprising conclusion, namely that furnaces with a more complex structure and equipped with canal-pits may in fact represent a relatively lower level of technological knowledge and skill on the part of the ancient smelters. Using them was not a result of technological progress but rather counteracting some limitations that enforced obliged the smelters to use such devices. The fact that they appear to have been abandoned in the structures that represent the climax in the development of iron metallurgy of the Przeworsk culture implies the elimination of some problems that had forced the smelters to employ such time-consuming and frequently fairly complicated technological solutions. A regular pit in which a perfectly liquefied slag block was formed with a clearly marked surface of solidification serves as proof that smelters had mastered a very complicated bloomery process. Conducting a smelting process in furnaces devoid of various supporting elements, such as those undoubtedly represented by canal-pits, bears witness to the genius of the prehistoric smelter.

References

Bielenin, K. 1973, 'Dymarski piec szybowy zagłębiony (typu kotlinkowego) w Europie starożytnej', *Materiały Archeologiczne* 14, 5–101.

Bielenin, K. 1983, 'Der Rennfeuerofen mit eingetieftem Herd und seine Formen in Polen', *Offa* 40, 47-61.

Bielenin, K. 1992, *Starożytne górnictwo i hutnictwo żelaza w Górach Świętokrzyskich*, (Kielce).

Bielenin, K. 2002, 'Kilka dalszych uwag dotyczących starożytnego hutnictwa świętokrzyskiego', in S. Orzechowski (ed.), *Hutnictwo świętokrzyskie oraz inne centra i ośrodki starożytnej metalurgii żelaza na ziemiach polskich* (Kielce), 11-25.

Bielenin, K. 2005, 'Kloc żużla dymarskiego z Boleszyna. Uwagi o znaczeniu badań powierzchni kloców żużla dymarskiego', *Materiały Archeologiczne* 35, 189-198.

Domański, G. 1972, 'Stanowisko hutnicze i osady z Tarchalic, pow. Wołów, stan.1', *Sprawozdania Archeologiczne* 24, 391-438.

Hayen, H. 1968, '„Isarnbarg" – Ein Eisenhüttenplatz im Streeker Moor (gemeinde Hatten), Lankreis Oldenburg)', *Oldenburger Jarhrbuch* 67, 133-173.

Orzechowski, S. 2006, 'Wyniki najnowszych badań na stanowiskach osadniczych i produkcyjnych świętokrzyskiego centrum hutniczego', in S. Orzechowski & I. Suliga (eds.), *50 lat badań nad starożytnym hutnictwem świętokrzyskim. Archeologia – metalurgia-edukacja* (Kielce), 33–73.

Orzechowski, S. 2007a, 'The region of iron: the Przeworsk Culture iron producing centre in Barbaricum', in P. Crew & S. Crew (eds.), *Early ironworking in Europe II, archaeology, technology and experiment.* Second International Conference Plas Tan y Bwlch Sept. 2007 Wales (Plas Tan y Bwlch), 27-28.

Orzechowski, S. 2007b, *Zaplecze osadnicze i podstawy surowcowe starożytnego hutnictwa świętokrzyskiego* (Kielce).

Pleiner, R. 1958, *Základy slovanského železářského hutnictví v českých zemích* (Praha).

Pleiner, R. 2000, *Iron in Archaeology. Early European Bloomery Smelters* (Praha).

Pleiner, R. 2006, 'Piece typu zagłębionego na terenie Europy w okresie wpływów rzymskich', in S. Orzechowski & I. Suliga (eds.), *50 lat badań nad starożytnym hutnictwem świętokrzyskim. Archeologia – metalurgia-edukacja* (Kielce), 137–149.

Suliga, I. 2006, 'Próba metalurgicznej weryfikacji koncepcji archeologicznej K. Bielenina „powierzchni swobodnego krzepnięcia" starożytnych kloców żużlowych, na podstawie kloca z Kowalkowic, gm. Waśniów', *Materiały Archeologiczne* 36, 267-272.

Tomczak, E. 2007, 'Starożytne centrum metalurgiczne koło Warszawy. Zagadnienia dyskusyjne', *Archeologia Polski* 52 (1-2), 177-186.

Weiershausen, P. 1939, 'Vorgeschichtliche Eisenhütten Deutschlands', *Mannus-Bücherei* 65 (Leipzig)

Woyda, S. 1977, 'Mazowiecki ośrodek hutnictwa starożytnego (I wiek p.n.e. – IV wiek n.e.)', *Kwartalnik Historii Kultury Materialnej* 25

(4), 471–488.

Woyda, S. 2002, 'Mazowieckie centrum metalurgiczne z młodszego okresu przedrzymskiego i okresu wpływów rzymskich', in S. Orzechowski (ed.), *Hutnictwo świętokrzyskie oraz inne centra i ośrodki starożytnej metalurgii żelaza na ziemiach polskich* (Kielce), 121–154.

Woyda, S. 2005, 'Równina Błońska u schyłku doby starożytnej. Centrum metalurgiczne', in M. Dulinicz (ed.), *Problemy przeszłości Mazowsza i Podlasia* (Warszawa), 129-166.

The oldest iron smelting furnaces in Denmark

A. Jouttijärvi and O. Voss

The oldest Danish iron smelting furnace (Fig. 14) was excavated in 1966 at Skovmark, North Jutland, and radiocarbon-dated to 90–110 AD. It opened at the bottom into a working pit. In 1986 another furnace of the same type was excavated at Espevej, West Zealand, together with separate clay tuyères that were not found in situ. A reconstruction of this furnace was published (Fig. 18). The tuyère plate was placed close to the bottom of the furnace with an opening below it for removal of the slag. In this paper a new reconstruction is presented (Fig. 17) based on the excavation of a Skovmark furnace at Sønder Holsted, South Jutland, in 2000. It is our theory that the origin of the Skovmark furnace can be traced back to the South German furnaces from the La Tène period.

Iron smelting furnace - Reconstruction - Denmark - Pre-Roman Iron Age - Tuyére plates - Radiocarbon date

Introduction

The slag-pit furnaces in Denmark were, according to radiocarbon dates, in use from 140 to 610 AD, but prior to that time there were a group of older furnaces. The first of those (Fig. 14 /Plate VI/) was excavated in 1966 in North Jutland at a site called Skovmarken, not far from Aalborg, and it has been radiocarbon-dated to 90–110. These Skovmark furnaces from the Late Pre-Roman and Early Roman Iron Age are all found connected to settlements. In most cases, only 10–15cm of the bottom part of the furnaces are left. They usually contain only a small amount of slag, which often makes it difficult to recognize it as a part of an iron-smelting furnace.

Since 1966, about twenty sites with Skovmark furnaces have been found in Denmark. In 2000 at Sønder Holsted in the southern part of Jutland, we had the opportunity to excavate three more of these furnaces. One was partly destroyed because the pit had been dug into it and had taken away one side of the furnace (Fig. 15 /Plate VI/, photo and plan). In this secondary pit, an important fragment of the furnace was found; it

Figure 14: Skovmark, Aistrup parish, Aalborg county. Vertical photograph of the bottom of the furnace.

belongs to the transition from the shaft to the subterranean part of the furnace. This fragment constitutes almost one-third of the circumference of the furnace at the level of the bottom of the shaft. In the upper part, there is a narrow 15cm high piece of the shaft and a bigger piece below the surface of the ground measured down to 15cm. Here it is possible to make out solidified drops of slag on the way down into what we have called the 'slag drain'.

What was left of the furnace *in situ* was so badly damaged by cultivation that it could not be directly connected to the fragment found in the secondary pit. However, it is possible to estimate the distance from the bottom of the 'slag drain' and up to the ground level with the shaft. Judging from the height of the flagstones in the side of the opening at the bottom of the 'slag drain' this distance must have been more than 40cm. During the excavation, it was noticed that there was no vitrified area in the lower part of the 'slag drain'. This means that the air inlets (the tuyères) could not have been located here. This has also been observed at other

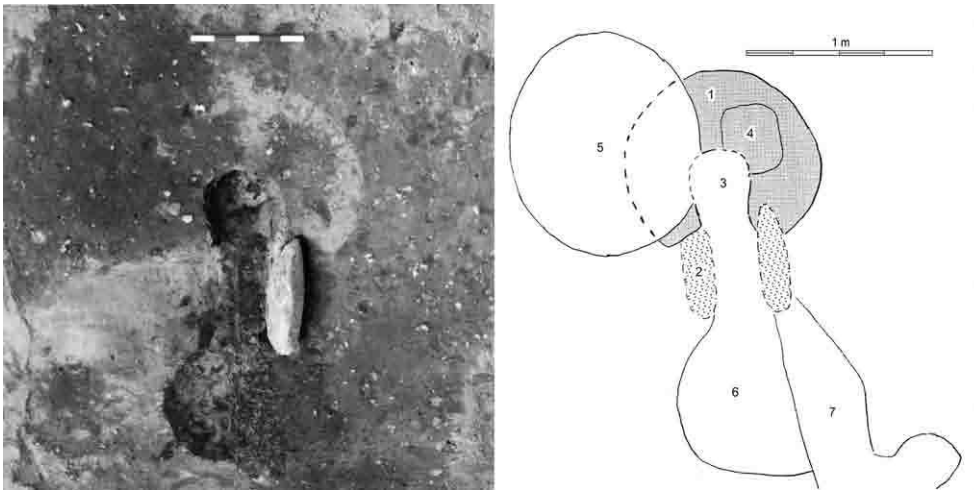

Figure 15: Sønder Holsted, Holsted parish, Ribe county: Vertical photo of furnace A105, partly excavated; plan of furnace A105 – 1: The clay packing, 2: Flagstones, 3: Slag drain, 4: Secondary disturbance, 5 The secondary pit, 6 The working pit, 7 Secondary disturbance. Scale 50cm.

Skovmark furnaces, but the implications of this observation had not been understood (Fig. 16) /Plate VII/, The emptied Sønder Holsted furnace A 186. On the fragment of the Sønder Holsted (2000, A104) furnace that was found in the secondary pit, it can be seen that there has been an air inlet in the south side slightly above ground level. A similar air inlet was probably located symmetrically on the north side. Judging from the layers of slag on the inside of the shaft, it could be seen that three smelts had taken place. The same secondary fragment shows that the clay-built shaft had a diameter of 30–35cm at the bottom.

With the information gained from the excavation of this furnace from Sønder Holsted, we have produced a new reconstruction of the Skovmark furnace type (Fig. 17). The whole shaft is above ground level and below it is the 'slag drain' with an opening at the bottom where the slag can be removed to the working pit.

Following this reconstruction of the Sønder Holsted furnace, it was necessary to reconsider the documentation on the furnace from Espe on West Zealand excavated in 1986 and reconstructed in 1987 as shown in Fig. 18 (Andersen *et al.* 1987, 179, fig. 308:6) and in Voss (1989). It became clear that this reconstruction is incorrect and that the Espe furnace could be reconstructed in the same way as the furnace from Sønder Holsted. There was no vitrified area in the underground part of the Espe furnace: what was excavated was the 'slag drain'. The tuyère plates, Fig. 19 /Plate VII/, being heavily vitrified must have been placed above ground level at the lower part of the shaft. What was excavated at Skovmark in 1966 was also

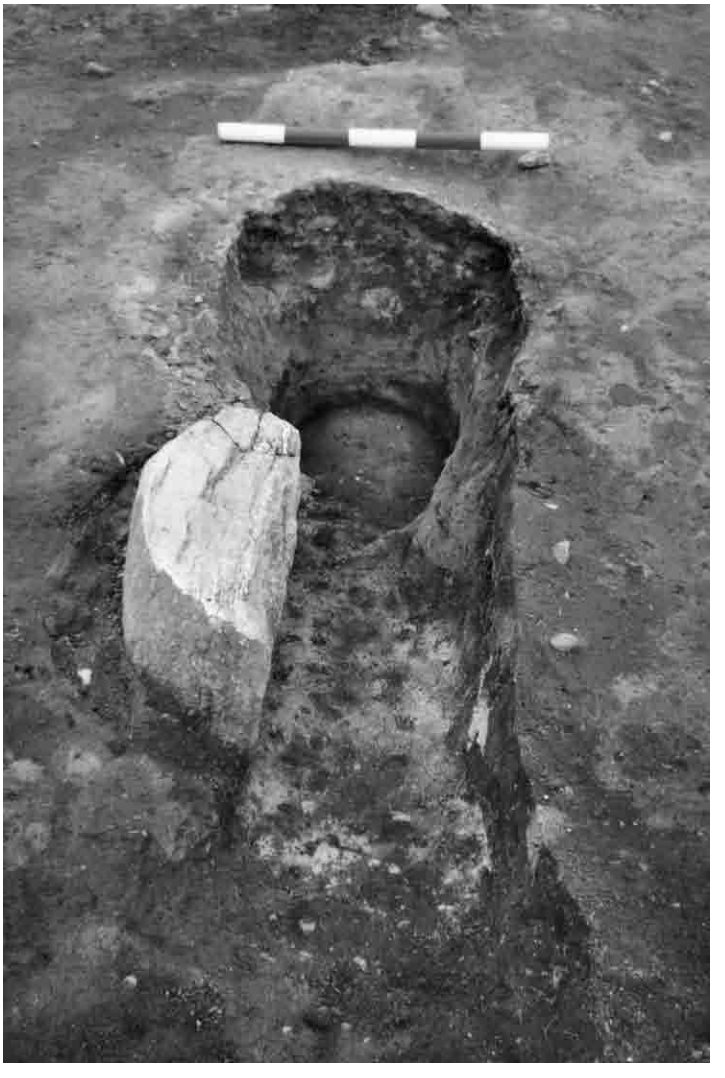

Figure 16: Sønder Holsted, Holsted parish, Ribe county: Furnace A187 after excavation. Scale 50cm.

only the lower part of the 'slag drain' and the opening for the slag out to a working area in front of the furnace (Fig. 14 /Plate VI/).

The smithy huts at Snejbjerg near Herning, Middle Jutland

In 1999 Herning Museum excavated three Skovmark furnaces at Snejbjerg. Each of them was situated in the southern part of a smithy hut, which also contained a forge and an anvil. These huts were almost 6m long with two pairs of roof-bearing posts and with an entrance to the forge at

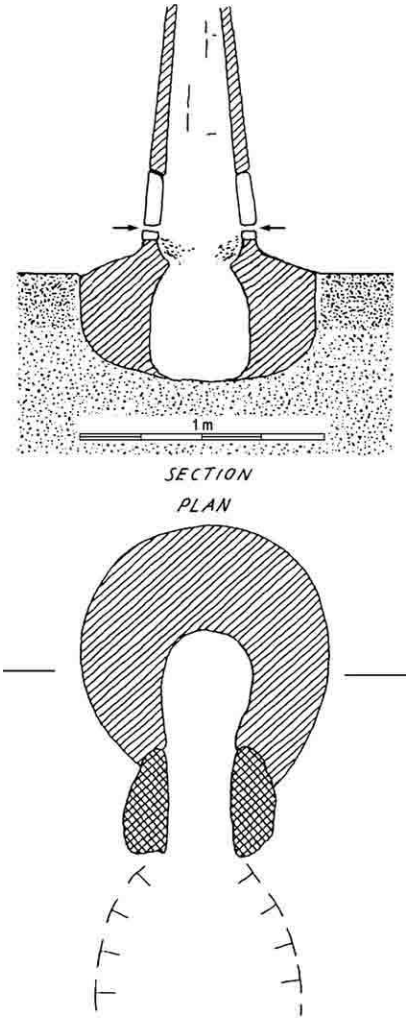

Figure 17: Sønder Holsted: Reconstruction of the Skovmark-type furnace.

the northern end, fig. xx. 'Plan of Hut 2101' (Olesen 2000). This is the first time it has been recorded that a Skovmark furnace was a part of a smithy hut, but it is possible that there might have been similar huts at other sites that have not been recognized.

The occurrence of Skovmark furnaces in Denmark

The occurrence of Skovmark furnaces in Denmark shown on the map (Fig. 21) is not representative of their distribution. This is caused by the levelling of the landscape as a result of cultivation and erosion, which is

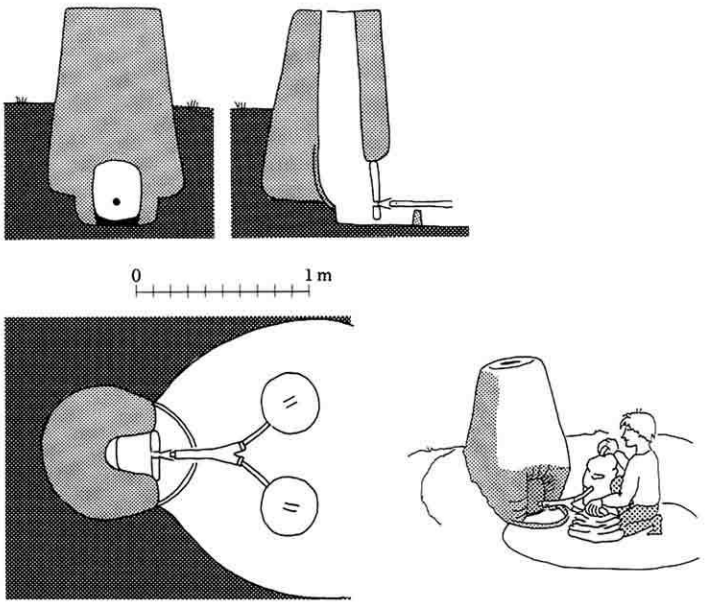

Figure 18: Espe, West Zealand: 1987 Reconstruction of the furnace.

more pronounced in the eastern part of Denmark.

The excavations have shown that only 10–15cm or less remains of the 40–50cm deep 'slag drains' and that those remains contain only a small amount of slag. In many cases, therefore, it has not been possible to recognize them as part of iron-smelting furnaces, especially if the topsoil had been removed by machine. In Jutland, where the levelling of the landscape has not been so strong, the furnaces are better preserved and therefore more have survived here.

In Norway and Sweden similar furnaces have been found, also from the Pre-Roman Iron Age and often with a stone lined slag drain.

Early iron-smelting furnaces in Northern Europe

In continental Europe the furnaces from Ořech near Prague (Fig. 22: Motyková & Pleiner 1987) and from Gera-Tinz in Thuringia (Dušek 1967) might be similar to the furnaces from Sønder Holsted and Espe. At both Ořech and Gera-Tinz the furnaces were built into a subsoil of loess and they were preserved to a depth of 50cm. What has been excavated at these two sites could also be 'slag drains' with the opening at the bottom for the removal of the slag. At neither of these sites was a vitrified area close to the bottom recorded. This would be expected if the opening had also been an air inlet.

Figure 19: Espe, West Sealand. Inner side of clay tuyère plate.

It is our theory that the origin of these early furnaces with 'slag drain' could be Celtic furnaces (like those excavated in south-west Germany by Gassmann (2005) and dated to 550–400 BCE at 'Neuenburg' and to the 4th–3rd centuries BCE at St Johan–Würtingen. The plans and photographs (Gassmann 2005, fig. 7.20, 7.22 and 7.23 and fig. 7.32) of these furnaces are to us very similar to the Skovmark furnace, but they have been reconstructed with a cupola like Pleiner's domed furnaces (Pleiner 2000, 163f.). The reason for Gassmann's reconstruction of the furnace with a cupola might be that the heavy clay packing around the furnace has been regarded as the base for a cupola. Gassmann refers to this area as the *Brennraum*, i.e. where the temperature was highest.

Gassmann's furnaces and the furnaces from Ořech and Gera-Tinz, and possibly also those from Engsbach and Minnerbach, are decisive for the theory of the possible Celtic origin of the Skovmark furnace and some of the Scandinavian early iron-smelting furnaces. The furnaces from Engsbach and Minnerbach might belong to the same group, but they were excavated in the 1930s and, as Martin Kempa wrote in 1995, "it would be desirable with modern methods to excavate preserved furnaces from the

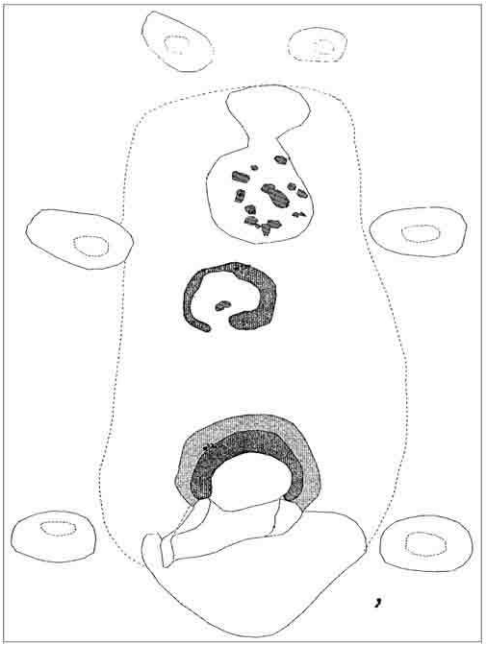

Figure 20: Snejbjerg, near Herning, Jutland: Plan of smithy hut.

La Tène period to obtain a better understanding of the often strange and complicated results from the old excavations as the ones from Minnerbach and Engsbach."

What Kempa points out here is the problem regarding the documentation of the excavation of iron-smelting furnaces (which is also treated by Pleiner 2000, 412): "In archaeological excavations thousands of smelting furnaces have been investigated, but the finds are normally so fragmentary that it is difficult or impossible to reconstruct the shape of the furnace. It is in any case the objective of every excavator to be able to propose a reconstruction. Because of the fragmentary state of the furnace it is necessary to be critical of all attempts of reconstructions. When reconstructions are published it should always be together with the documentation in form of drawings and photos."

Many reconstructions of furnaces are presented without any documentation, thereby making it impossible to judge their reliability. In our opinion, this has resulted in a maybe too large number of furnace types. New excavations and better documentation might reduce the number of furnace types and at the same time make it possible to trace their history.

It is our theory that furnace A104 from Sønder Holsted and the other Skovmark furnaces might be of the same type as the furnaces from Ořech and Gera-Tinz, and also similar to the older excavations from Ensgbach and Minnerbach, and that they are all in some way connected to the Celtic

Figure 21: Denmark: Sites with Skovmark furnaces. 2nd century BCE to 2nd century AD.

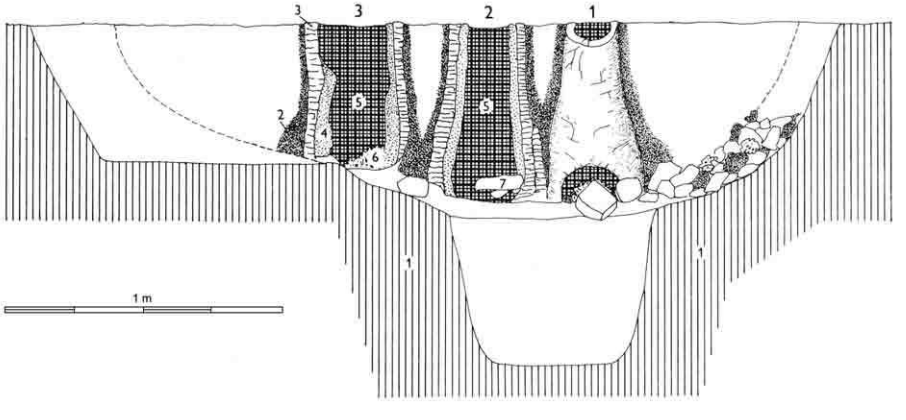

Figure 22: Ořech, near Prague: Iron-smelting furnaces (after Motyková & Pleiner 1987).

furnaces from Bayern-Württemberg. Only future excavations will be able to show how viable this idea is.

References

Andersen, A.H. et al. 1987: Andersen, A.H., Kaul, Fl. & Voss, O. 1987, 'Danmarks ældste jernudvindingsovne', in *Danmarks længste udgravning*, 176-180.

Behagel, H. 1939, 'Eine latènezeitliche Eisenverhüttungsanlage in der Minnerbach bei Siegen', *Germania* 23, 228-237.

Dušek, S. 1967, 'Eisensmeltzöfen einer germanischen Siedlung bei Gera-Tinz', *Alt-Thüringen* 9, 95-183.

Gassmann et al. 2005: Gassmann, G., Hauptmann, A., Hübner, Ch., Ruthardt, T., Yalcin, Ü., 'Forschungen zur keltischen Eisenverhüttung in Südwestdeutschland', in *Forschungen und Berichte zur Vor- und Frühgeschichte in Baden-Würtemberg* Band 92.

Gilles, J.W. 1936, 'Die Grabungen auf vorgeschichtlichen Eisenverhüttungsplätzen des Sigerlandes', in *Stahl und Eisen* 56, 252-263.

Kempa, M. 1995. 'Die Ausbeutung der Erzlagerstätten in vor- und frühgeschichtlicher Zeit', in *Beiträge zur Eisenverhüttung auf der Schwäbischen Alb. Forschungen und Berichte zur Vor- und Frühgeschichte in Baden-Württemberg* 55 (Stuttgart), 311-336.

Motyková, V. & Pleiner, R. 1987, 'Die römische Siedlung mit Eisenhütten in Ořech bei Prag', *Památky Archeologické* 78, 371-448.

Olesen, M.W. 2000, 'Tre smedjer fra Snejbjerg', in *Fra Ringkøbing Amts Museer 2000* (Herning), 23-36

Pleiner, R. 2000, *Iron in Archaeology. Early European Bloomery Smelters* (Praha).

Stieren, A. 1935, 'Die Vorgeschichtlige Eisentechnik in Südwestfalen', *Germania* 19, 12-20.

Voss, O. 1989, 'Iron Furnaces in Denmark', in R. Pleiner (ed.), *Archaeometallurgy of Iron 1967-1987* (Prague), 153

Archaeometallurgy in Hungary: some results and questions

J. Gömöri

Newly discovered Avar iron production centres were excavated in the large areas of motorway construction in Transdanubia. There are two important periods of iron production in this part of Pannonia: the earlier one is connected with the middle and late periods of the Avar Empire, from the 7th to 8th centuries AD up to the Carolingian period in the 9th century. The later period began with the founding of the Hungarian state in the 10th century. Up to the present two sites where furnaces were found from both periods are known. The first result of the most recent archaeometallurgical research is that Avar ironmaking was more significant in Pannonia than previously thought. These extensive centres of iron production and smithing (possibly of weapons) may have been directly in the zone in which the Avars came together, to organize campaign against Byzantium on the line of the main Roman roads. A further question relates to the origins of Pannonian Avar iron metallurgy. Our present knowledge suggests that iron production has no local antecedents from the Roman period. One of the results of the new excavations is correction of dating of the supposed Roman age furnace at Sopron to the 11th–12th century.

Pannonia - Roman period - Avar - Iron production - Bloomeries - Tuyères

New results from south of Lake Balaton

Some new discovered Avar iron production centres were excavated in Somogy County by the Somogy County Museum, with Zsolt Gallina as the director of the excavation. Only short preliminary reports have been published of this research, carried out on the plains of the Zamárdi-Kútvölgy (Gallina, Hornok & Somogyi 2007) and Kaposvár-Fészerlak-puszta sites (Gallina 2002).

In 1986–87 the first professional archaeometallurgical excavation in Somogy County was carried out at the village of Zamárdi (Gömöri 2000), close to the southern shore of Lake Balaton, which resulted in the discovery of an important iron-producing centre from the late Avar period. Remains of two furnaces and eleven roasting pits or the bases of charcoal-burning

pits along of the Kútvölgyi brook were found in the vicinity of a large Avar cemetery (with 2300 graves) of Zamárdi-Rétiföldek (excavated by E. Bárdos). Professor I. Bóna believed that an early kind of town (ordu), an Avar centre, was located next to these two sites. The craftsmen's unit was situated at a distance, but not too far away from the wooden buildings, yurts, and small houses dug into a large Avar centre. According to radiocarbon dating the site dates from between 734 and 770 (E. Hertelendi, Debrecen). Archaeomagnetic study places it between 734–770 and 580–850 (P. Márton).

Fortunately, during the building of a motorway in 2002 Zsolt Gallina was able to excavate more of this Avar 'industrial' quarter. The neighbouring sites (Nos. 56, 58a, 58b, and 89) at Zamárdi-Kútvölgy which produced 580 Avar objects, indicate one of the largest archaeometallurgical sites in Central Europe. The settlement, which was inhabited between the 7th to 9th centuries, was one of the supply villages of the main Avar centre in Zamárdi. Excavations revealed seventeen iron-smelting furnaces, nearly a hundred ore-roasting hearths, the bases of charcoal-burning heaps, three reheating hearths, and a smithy, all located between the dwelling houses, the hundred bakers' ovens, and various pits at this early medieval village. The clay loom weights and the grinding stones in the houses indicated the rural characteristics of the inhabitants. The furnaces, with base diameters of about 40–45cm, were partly built into banks and partly free-standing, like the Avar furnaces in north-western Transdanubia and in Somogy County (e.g. Magyaratád: Gömöri 2000). In some cases the metallurgical furnace had a roof cover supported on four posts (Gallina, Hornok & Somogyi 2007).

Another large Avar iron-production centre in Somogy County was found in 2001 during construction of the main road No 61 built to bypass the town of Kaposvár. During the fieldwork an area of 17.500m^2 was uncovered on site 19 at Fészerlak puszta. Some 425 objects were found in this area, including some 2–3m long and 1.5–2m wide oval ore-roasting pits, the remains of 37 partly free-standing bloomery furnaces with a base diameter of 30–45cm, and round reheating hearts. According to the director of the excavation the metallurgical 'furnaces were situated in a haphazard fashion, sometimes forming smaller groups. The majority were demolished during the Avar period. In one case we were able to trace the oval roof over a smelting furnace and a reheating hearth' (Gallina 2002). Two sunken dwelling houses, remains of timber-framed buildings (postholes), five wells with wooden structures, and various pits served the ironmakers at this settlement, but no vestiges of a typical rural village came to light at this metallurgical centre, which can be dated to the 7th–9th centuries. The associated villages were possibly situated nearby, because 'south and

west of the iron producing furnaces, at a distance of 0.5–1.5km, three Late Avar cemeteries have been excavated' (Gallina 2002).

The third extensive metallurgical centre lies at Magyaratád-Kéri határra dűlő (1999). A complex of irregularly shaped pits full of iron slag was discovered on the long slag site, with remains of a house (280cm - 350cm basic area, with stone oven). An Avar-type furnace, which was practically free-standing but partly built into the earth, was found among the pits, which were bordered by a double ditch sloping towards the brook. There was a shallow slag-tapping pit in front of them, with diameters between 50cm and 105cm. The following dates are proposed: the furnace (radiocarbon) 625–657, 586–673; the house (radiocarbon) 462–498, 513– 576, 444–; pit No. 7 (from Avar hand-made ceramics) 579–659, 458–497, 513–687 (Zsuzsanna Szánó, Debrecen, ATOMKI); archaeomagnetic dating before 850 (Péter Márton, ELTE), (Gömöri 2002).

The fourth important rescue excavation is in progress near Bátaszék in Tolna County. The director of the excavation, Attila Czövek found the first discovered Avar metallurgical site in this county in 2008, with around 19 bloomery furnaces built into banks (this excavation has not yet been published). The Avar furnaces in Somogy County (Magyaratád, Zamárdi-Kútvölgy, Kaposvár-Fészerlak) and Tolna County (Bátaszék) were located in various groups, partly dug into the earth, and there was a slag-tapping pit in front of them. Blowing also was carried out from this pit. Around the furnaces there were ore-roasting pits, and in many cases the houses, pits, and ditches of a rural village.

These extensive centres of iron production and possible forging of weapons may have been created in the Avar military grouping zone, created to organize the campaign against Byzantium along the routes of the main Roman roads. 1: Kaposvár and Magyaratád are situated near the Savaria (Szombathely)–Valcum (Keszthely–Fenékpuszta)–Sopiane (Pécs) main road. 2: Zamárdi, not far from the Late Roman fortress of Tricciana (Ságvár), lies near the main road from Arrabona (Győr) to Sopiane. 3: Bátaszék is located near the *ripa Pannonica*, the *Limes* road Aquincum (Óbuda)–Brigetio (Dunaújváros)–Lussonium (Paks)–Mursa (Osijek/Eszék, Hr) and close to the another north–south road Brigetio (Ószőny)–Gorsium (Tác) crossing the *Dravus flumen* and thence via Mursa, Cibalae, Sirmium to cross the Danube into the Byzantine Empire. This route was later used as a military route by the Ottoman army from Constantinople against the Hungarian Kingdom in the 16th century.

The spreading of the Avar-type furnaces can be dated to the period of the Onogur colonization of Pannonia in the Middle and Late Avar Period (after 670) and was also used in the 9th century (Nemeskér-type furnaces), when north-western Pannonia (as a part of the Ostmark) was a controlled

military border zone of the Frankish alliance. The ironmakers living in the western area of the former Avar Empire were possibly obliged to supply the Carolingian Frankish-Bavarian land organization (Gömöri 2000). The Somogyfajsz-type workshops south of Lake Balaton, with operations concentrated in large work pits, are supposed to be later than those of the Avars. Some 43 iron-smelting furnaces and two baking ovens were found at Bodrog-Alsóbű-puszta (Gömöri 2000, fig. 13). We conclude that the organization of work was different at the two iron-smelting communities. On the basis of the runic-like writing preserved on a tuyère in Bodrog-Alsóbű, it is presumed that most of the metal workers in this workshop were Hungarian (Sekler?) (Gömöri 2000, fig. 11). The site is dated by the radiocarbon method: furnace No. 10: 717–728, 752–879, 682–922, 927–951; baking oven No. 15: 713–846, 673–905) (Zsuzsanna Szántó, Debrecen). Archaeomagnetic dating assigns it to the beginning of the 10th century (Péter Márton).

New results in Sopron County

Two iron-smelting furnaces were excavated by the author in 2000 at Zsira (Sopron County). They were situated directly next to a stone wall of the main buildings of a Roman period *villa rustica*, which was investigated by G. Gabrieli. The earliest furnace was a typical Avar one. P. Márton (ELTE) used archaeomagnetic dating to determine that it dates from c. 8th century. The other one was a thin- walled shaft furnace set into a bank that had been rebuilt a number of times (charcoal found in the large working pit of this furnace was radio-carbon dated to the Árpád period, according to É. Svingor, Debrecen).

Between the iron-production sites nearer Sopron there is another location, in the Potzmann field, where Avar-type furnaces and ore-roasting pits were discovered next to a later 10th century workshop. This site is located near the former (now ruined) *terra Kovácsi* with a slag site. The iron-making sites are located regularly along the Rák brook. The first one lies at the Bánfalvi street with coupled furnaces in a rectangular bloomery-workshop and a dwelling house nearby Fig. 23: 7 /Plate VIII/), (10th–11th century, excavated in 1972 by the author). The last one is the iron-ore pit field in woodland beside the village of Kópháza, and a Nemeskér-type (?) furnace together Fig. 23:1 /Plate VIII/) (radiocarbon dating: 990 /110, after Éva Csongor, Debrecen 491), while the centre of the estate was probably located in the fortress of Sopron (Fig. 23: 6 /Plate VIII/).

In 1955 one of the first published (Nováki 1968, fig. 28) iron bloomery furnaces in Hungary was discovered in Sopron, Deák square (formerly

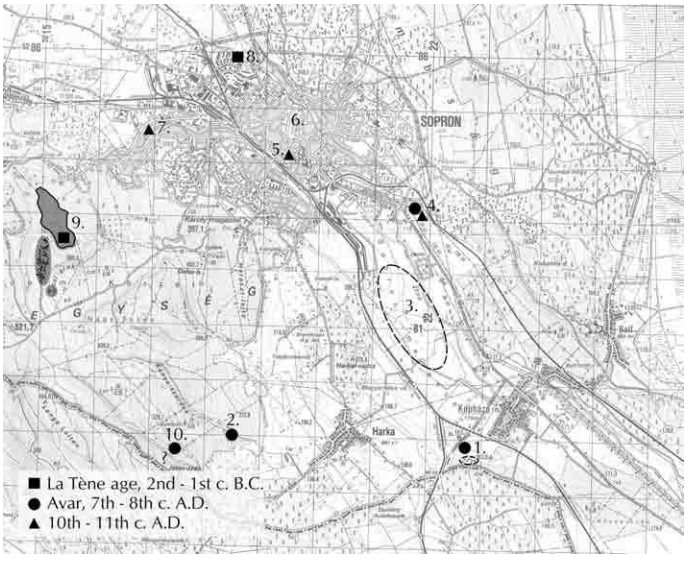

Figure 23: Iron production sites near Sopron. 1: Kópháza, minepit field (Avar? - Medieval) and a metallurgical furnace (J. Gömöri 1999); 2: Harka–Kányaszordok (Bikarét), free-standing furnaces built of stone (Avar) (J. Gömöri 2000); 3: *terra Koachi... que fuit fabrorum castri Supruniensis* (1268); 4: Potzmann dűlő (balk), Avar and 10th century furnaces, ore-roasting pits (J. Gömöri 1999); 5: Deák tér (square), 11th century bloomery workshops (M. Radnóti, Gy. Nováki 1968, G. Gabrieli); 6. The fortified Scarbantia (4th century) and the Árpád age castrum Supron (late 10th century–1277), the medieval inner town (J. Gömöri 2002); 7: Bánfalvi út, 10th–11th century bloomery and dwelling house (J. Gömöri 1973); 8: Krautacker, Celtic settlement with an 'industrial quarter,' an iron-reheating furnace and some pottery kilns (J. Gömöri 2002, E. Jerem); 9: Sopron–Burgstall, Hallstatt period, and late La Tène age hillfort, sporadic iron slags (E. Patek); 10: Magas-híd, slag heaps with early medieval tuyère panels made of clay (Gy. Nováki 1958). (Base map: M. Honv. Térk. Hiv.1: 25000, Sopron-Nekenmart, reduced detail. Constructed by J. Gömöri 2009).

Sztálin tér, Május 1. tér) very near the old Roman *castrum*, between the earlier cremation burials and the late Roman inhumation graves of the south cemetery of Scarbantia Fig. 23: 5 /Plate VIII/). The dating of the furnace was uncertain: 27 year after it was excavated by M. A. Radnóti thermoluminescence dating of the burnt clay sample from the wall of the shaft was carried out by L. Benkő (1984), in the exhibition hall of the Sopron Museum, since it was impossible to use local detectors on the site. The archaeologists generally accepted the initial age determination as the 3rd century AD because inhumation ceased in this cemetery and the area was used by potters, as shown by the pottery kilns that were excavated. Others refer to the similarity in form between this 'Roman' furnace and the early medieval 'Imola-type' embanked furnaces with thin front walls (Nováki 1968, Gömöri 1973, Gömöri 2000). The conclusion of the rescue

excavation (directed by G. Gabrieli, in consultation with the author in 2006) was that this furnace was used in the period of establishment of *castrum Suprun* (Sopron). Very similar remains of four furnaces were found in the newly excavated workshop, on the other bank of the Rák brook (Fig. 24 /Plate IX/). The workshop was enlarged once by building new coupled furnaces into the sides of the pits (Fig. 25: A and B /Plate X/). The bloomery was dated to the late 11th century or early 12th century by ceramic typology and radiocarbon analysis (1130 ± 35, É. Svingor, Debrecen). The director of the excavation discovered another workshop behind the bloomery, with an untypical oval furnace with a longer diameter of 120cm. The base of the hearth is very little burnt, but the back side is hard-burnt red. The thick charcoal layer indicates that this hearth possibly served for ore roasting or bloom hardening. There is only one analogy for this hearth (Fig. 26): from the iron production site at Röjtökmuzsaj (Gömöri 2000, fig. 103, 106), and a distant similar, but smaller, round-shaped object in Gajvoron (Ukraine) dated to the 7th century (Pleiner 2000, fig. 28, 1). Our hearths differ from the two bakers' ovens found between the bloomery furnaces in Bodrog-Bű puszta (early 10th century) because those bases were even and very hard-burnt.

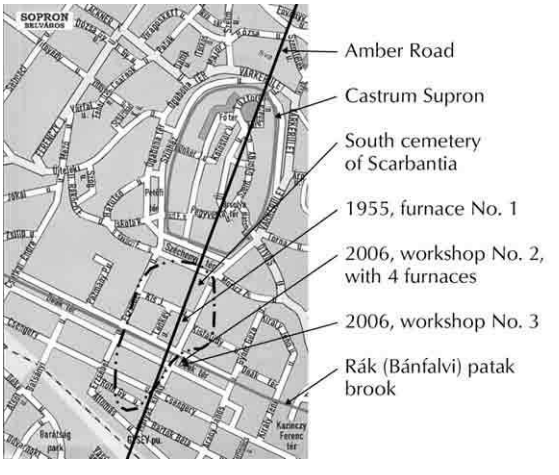

Figure 24: The location of the workshops near the brook, south of the *castrum* with red burnt rampart behind the Roman period stone wall. (Scale: the fortification marked in red is 400m long and 250m wide. Constructed by J. Gömöri 2009).

As a result of this excavation we can prove that up to the present no unambiguous traces of iron production have been found in the Hungarian part of the Roman province of Pannonia. This province had to import iron, mostly from Dalmatia and possibly also from Noricum, Dacia (?), and from Celtic (Cotini) territories adjacent to the Roman Empire through long-distance trade.

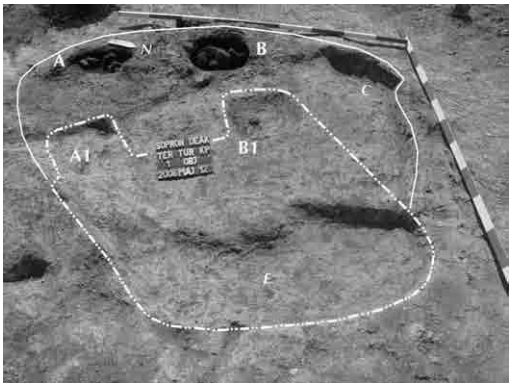

Figure 25: Sopron, Deák tér. Bloomery No 2 (= 2006/1 obj.) with paired, thin-walled, embanked, shaft furnaces. Broken line shows the Period I.: bottom of coupled furnaces (A1 and B1), entrance (E). Period II.: enlargement of the workshop, furnaces (A, B), ore- and charcoal-storage niche. (Photograph by G. Gabriella, interpreted by J. Gömöri).

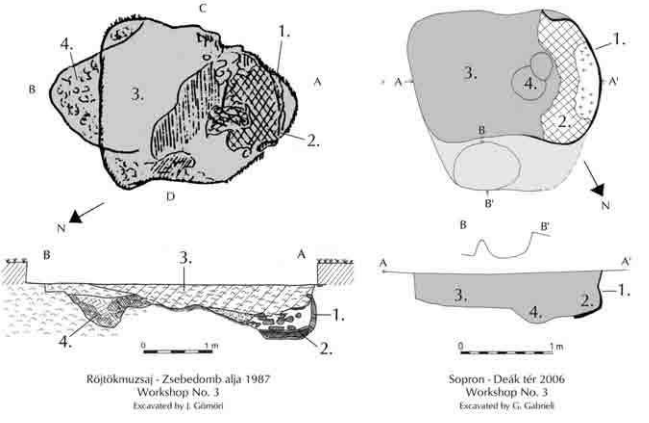
Röjtökmuzsaj - Zsebedomb alja 1987
Workshop No. 3
Excavated by J. Gömöri
Sopron - Deák tér 2006
Workshop No. 3
Excavated by G. Gabrieli

Figure 26: Two similar hearths, vaulted kilns made of clay, with a thick charcoal layer on the bottom, possibly for ore roasting or bloom hardening. Western Hungary, 11th century. 1: the heavily burnt side of the kiln; 2: a slightly burnt base, with thick charcoal layer; 3: working pit filled with mixed slaggy earth; 4: deepening (measured by J. Gömöri and G. Gabrieli).

Acknowledgments

Many thanks to my colleagues Attila Czövek and Zsolt Gallina for sharing information following their excavations in Bátaszék, Kaposvár, and Zamárdi. I also offer warm thanks to Gabriella Gabrieli, who handed over her publication rights in connection with the bloomery in Sopron, in exchange for the documentation of my excavations. Thanks to Professor Academic Péter Márton for the archaeomagnetic dating and to Dr

Zsuzsanna Szántó and Dr Éva Svingor for the radiocarbon date determinations (ATOMKI, Hungarian Academy of Sciences, Debrecen). I also wish to thank Dr Richard von Fuchs for the reading my English text and to Mihály Göbölyös for the computer design of the illustrations.

Last but no means least, my thanks go to Prof. Dr. Radomír Pleiner for the friendly exchanges of experiences on the occasion of various archaeometallurgical symposiums.

References

Benkő, L. 1984, 'Sopron, Május egy téri kemence TL vizsgálata. TL Dating of an Iron smelting Furnace found in the Roman Cemetery of Scarbantia', in J. Gömöri (ed.), *Iparrégészet, Industrial Archaeology II* (Veszprém), 139-140.

Czövek, A. 2008, 'Avar kori vaskohókat találtak az M6-os alatt', <http://www.mult-kor.hu/cikk.php?id=20457>

Gallina, J., Hornok, P. & Somogyi, K. 2006, 'Előzetes jelentés a Zamárdit elkerülő 65101. sz. út Zamárdi 89, 58a, 58b, 56. lelőhelyeinek feltárásáról. (Preliminary report of the excavations of the sites No. 89, 58a, 58b, 56. on the encircling road No. 65101 around Kaposvár.)', in *Somogy Megyei Múzeumok Közleményei* 17 A (Kaposvár), 153-168.

Gallina, Z. 2002, 'Avar kori kohótelep Kaposvár-Fészerlakon', in *Somogyi múzeumok közleményei* 15, 75-86.

Gömöri, J. 1973, 'Korai császárkori és Árpád-kori település, X. századi vasolvasztó műhely Sopronban', in *Arrabona* 15 (Győr), 69-123.

Gömöri, J. 2000, *Az avar kori és Árpád-kori vaskohászat régészeti emlékei Pannoniában: Magyarország iparrégészeti lelőhelykatasztere I. Vasművesség* (Sopron).

Gömöri, J. 2000/B, 'Überreste des römerzeitlichen Eisenverhüttungswesen und Schmiedehandwerkes in Pannonien und in den benachbarten sarmatischen Gebieten (Kurzfassung)', in H. Friesinger, K, Pieta & J. Rajtár (eds.), *Metallgewinnung und -Verarbeitung in der Antike (Schwerpunkt Eisen)* (Nitra), 117.

Gömöri, J. 2002, *Castrum Supron. Sopron vára és környéke az Árpád-korba* (Sopron).

Nováki, Gy. 1968, 'A magyarországi vaskohászat régészeti emlékei', in G. Heckenast, Gy. Nováki, G. Vastagh & E. Zoltai, *A magyarországi vaskohászat története a korai középkorban* (Budapest), 42-44.

Pleiner, R. 2000, *Iron in Archaeology. Early European Bloomery Smelters* (Praha).

Some aspects of the development of Great Moravian iron metallurgy

V. Souchopová, J. Merta and O. Merta

This paper introduces some of the findings of the latest stage of intentional research on the metallurgy of iron in the central part of the Moravian Karst, which began in the sixties of the last century. It includes a brief history of the project, identification and dating of the types of furnaces and ironworks, details of their distribution in space and time, and the method of their control. There has been progress on the question of the status of the mining-smelting district which, despite its geographical location, has in terms of total extent and work productivity and specialized production features, being assigned to Great Moravian power centres. Production and distribution of iron in this important pre-industrial area were presumably controlled by one of the Moravian centres, and the community of smelters most likely ranked among servants (familia) *belonging to one of the noblemen of the time.*

Moravian Karst - Metallurgy of iron - Bloomery - Space-time dislocation - Ducal family (familia) - Early medieval

Introduction

At the present time a summary and complete appraisal of the results of archaeological excavations of bloomeries in mining districts in the central part of Moravský kras (the Moravian Karst) from the 8th–11th centuries is being carried out. This paper outlines some of the knowledge that has been gained.

Right from the beginning, from the 1960s, research work was carried out as a part of a planned long–term project of archaeological excavation of bloomeries on the outskirts of Blansko. At that time it was announced that bloomery slags had been found in two different locations in the ore–bearing central part of the Moravian Karst (Souchopová 1970, 15–23). That alerted us to the possibility of gaining a certain amount of knowledge to complement earlier knowledge, with the help of archaeological excavations in more bloomery locations. The remains of old ironworks

had been found in the central part of the Moravian Karst, and researched even in earlier times, and for this reason we hoped to discover other findings and at the same time to learn from the results published by earlier researchers. Some older findings are quoted in J. Knies's work, but we gained the most knowledge from publications by J. Wankel, H. V. Sáňka, J. Skutil, and R. Pleiner.

The expectation of possibly finding new bloomery locations was fulfilled in later years. Since the 1960s two bloomeries from the end of the 8th to the beginning of the 9th centuries, two from the Great Moravian period, and nine more recent ironworks from the second half of the 10th to the end of the 11th centuries have been discovered and examined archeologically. From the start of the survey it was necessary to use the methods of the exact sciences to evaluate findings. Most importantly, metallography was used in the analysis of the objects that were discovered. Since 1972 we have also begun experimental iron smelting in small reduction furnaces, which were reconstructed on the basis of the discovery of their remains during archaeological excavation (Souchopová & Stránský 1989).

Smelting and mining centre in the Moravian Karst

The ore-bearing central part of the Moravian Karst was an important smelting and mining centre from the 8th until the 11th centuries. According to both our own and previous archaeological excavations, it is evident that the remains of early iron making are located in the area around the villages of Olomučany, Rudice, Habrůvka, Josefov, and Adamov; securely documented findings have also come from the area of the village of Babice (Fig. 27). Research has shown that separate bloomeries always operated for only a certain, short period and were then abandoned, most likely because wood species suitable for charcoal burning were cut down during the operation of the ironworks. Ceramic debris was mostly found in the slag heaps of bloomeries, which made possible to date individual ironworks. In bloomeries where furnaces were found it was also possible to identify the time period and types of furnaces, and even changes in the system of working in ironworks during specific periods connected with, for example, changes in the economic and political situation of the country. The stratification of ironworks into time periods, the discovery of more bloomeries in the area which made it possible to compare material among different workshops, and the discovery of ironworks in other areas of Europe brought some new information about the development of iron metallurgy in the four centuries mentioned above. An important fact is that these bloomeries were built in an environment of virgin forest where

no archaeologically involved human activity had taken place before. After the destruction of each separate ironworks, the area became covered in trees again and so no invasion of the locations took place. The ability to stratify the activities of different ironworks in terms of time has made the iron-producing centre in the central part of Moravsky kras into a sort of natural laboratory for exploring the development of ferrous metallurgy during this four-century period. Moreover, the iron production described took place there during a period of considerable political change, and it turns out that iron metallurgy responded readily to these changes in society (Souchopová 1992).

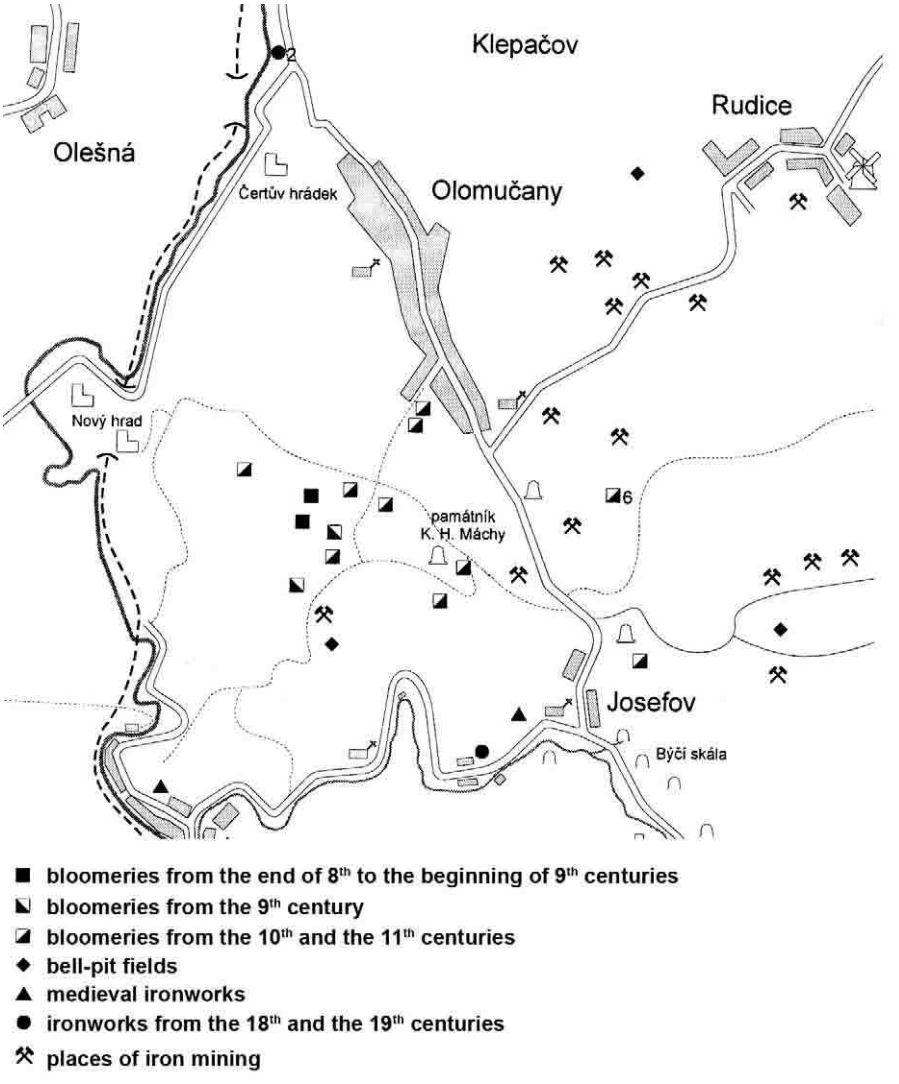

Figure 27: Schematic map of early medieval bloomeries in the central part of the Moravian Karst that were excavated from the 1960s. Drawing by J. Merta.

A global archaeological survey of ironmaking in the central part of the Moravian Karst was organized by the Department of Archaeology at the District Museum in Blansko in conjunction with scientists from some other organizations – the Technical Museum in Brno, the Archaeological Department at the Czechoslovak Academy of Science in Prague, the Polytechnic Institute in Brno, and the ČKD Blansko. From 1992 onwards these activities were concentrated in the Technical Museum in Brno, in conjunction with the survey and protection of more recent technical remains. One of them is Stará huť u Adamova (Old ironworks near Adamov, build at 1746 and working till 1877). At the present time, the ironworks area is used as a base for field research, and experimental iron smelting is carried out here as well. The area, which is dominated by the charcoal blast-furnace from the mid-19th century, also provided a place to build an open–air exhibition of experimental furnaces. Thanks to all of this, the ore-bearing central part of the Moravian Karst was included in an international project known as the European Iron Trail (Fig. 28 /Plate X/).

Figure 28: A view of the area of Technical Heritage Stará huť near Adamov. Iron-smelting experiments in reconstructed early medieval furnaces take place there. Photograph by J. Merta.

From the point of view of the chronological stratification of bloomeries found in the central part of the Moravian Karst, the oldest ironworks are dated to the end of the 8th and the beginning of the 9th centuries, followed by ironworks from the Great Moravian period from the second half of the 9th century. One interesting piece of evidence was the discovery of a hiatus in the building of ironworks, which started in the beginning of the 10th century and persisted for at least half to three-quarters of this cen-

tury. This is obviously due to the general situation in the country arising from the fall of the Great Moravian Empire. Its social and economic disintegration and the centralization of state power in Bohemia and Hungary probably caused the downfall of the Great Moravian type of iron metallurgy in the central part of the Moravian Karst. Ironworks that started operating in the central part of the Moravian Karst in the second half of the 10th century are so far the most numerous, but they were less productive than the Great Moravian bloomeries. The discovery of two pieces of a denarius of Ota I Sličný, domain duke of Brno and Olomouc who died in 1087, is very important for dating these more recent works.

Through gradually continuing surveys we learned about the spatio-temporal distribution of ironworks in the ore-bearing central part of the Moravian Karst. In the introduction we mentioned the surveys organized by previous researchers. In some cases we tried to trace these older archaeological excavations and to carry out exploratory sampling to obtain some details for comparison. Our work was in vain, however, because we were not able to find the locations of these former excavations in the wooded landscape. One ironworks can serve as an example: at the beginning of the 20th century H. V. Sáňka excavated it in the forest section of Padouchov in the Habrůvka cadastral unit, where we also dug in 1968–75 (Souchopová 1986, 46–53). In the area of our excavation of the bloomery we found no signs of earlier archaeological excavation even during a thorough external survey of the whole forest track. According to H. V. Sáňka, during his excavation embanked furnaces with thin frontal walls were discovered, which so far as we are aware date to the 9th century. However, in this wooded section we discovered ironworks that had worked in a later period (the end of the 10th and in the 11th centuries). This pointed to the possibility of repeated returns by ironworkers for iron smelting to places used previously. Following a series of completed excavations we were able to acknowledge that it is not exceptional to find ironworks from various time periods within a certain relatively small area. The bed of a stream which springs from U kukačky (the forest section of the village of Olomučany) provides a good example of the space–time (spatio-temporal) stratification of newly excavated ironworks (*ibid* 14). Remains of five ironworks from three time periods were found in this area (Fig. 29). A slag layer and ceramic debris were found opposite the spring on a slope which can be roughly dated to the end of the 10th to the end of the 11th century, but this spot was not excavated because of the dense forest cover. Suitable excavation conditions were found lower down the stream where two ironworks with furnaces of the Želechovice type from the end of the 8th to the beginning of the 9th centuries were discovered on its bank. Higher on the slope, an ironworks from the second half of the 9th century was located on

a platform cut into the hill. On a natural platform on the opposite bank lower down the stream there is a bloomery dated to the end of the 10th to the end of the 11th century. Searching lower along the stream banks did not reveal anything, but it is necessary to say that the field reconnaissance in the heavily wooded central part of the Moravian Karst generally does not bring any results. The wooded terrain does not provide any signs that would indicate the remains of old ironworks. We are restricted to accidental slag finds under roots of trees that have been blown down by the wind for discoveries of new locations.

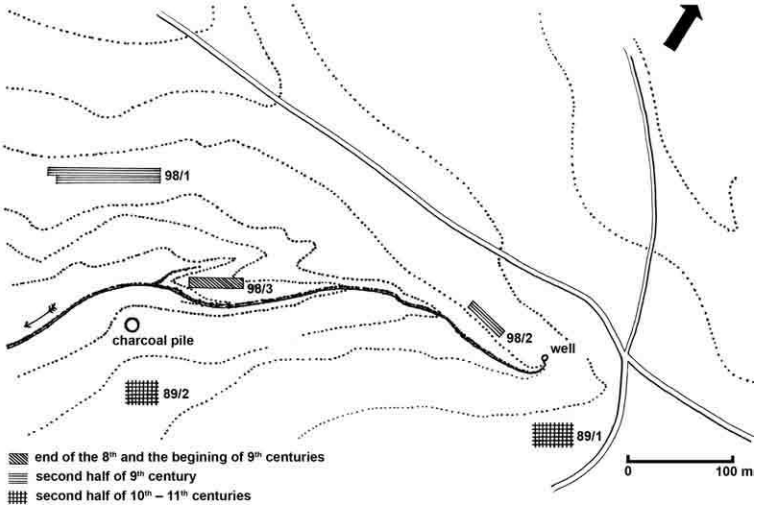

Figure 29: Schematic space–time map of bloomeries distribution near the spring called U kukačky (a forest section of the village of Olomučany). Drawing by J. Merta.

In all these cases a new bloomery did not occur exactly on the site of the ruins of older ironworks but nearby. Bloomery remains abandoned, for example, fifty years earlier could have given a guide to the foundation of new ironworks. Bloomeries were founded repeatedly on these places precisely because the locality was suitable for smelting. There was a source of water and a nearby source of clay, as well as an available pit field from which mined iron ore could be transported to the bloomery. A very important condition was sufficient wood for charcoal burning. If we assume that it was the cutting down of nearby tree species suitable for charcoal burning that was the reason for abandoning an older ironworks, it is evident that the 50–70 year interval after which a new bloomery appeared should be long enough for reforestation and necessary tree growth.

It should be understood that the iron-ore bed could be slightly remote from the ironworks. In the ironworks that were surveyed only ore that was ready for charging into the furnaces was found. The project considered ore samples from a bloomery from the end of the 10th and in the 11th

centuries on Růžová street in Olomoučany (Cad. Nos. 591/2 and 591/3; Souchopová 1986, 64–67). Layers of material made up of approximately 80% of sharp granular brown-red iron-ore sand, and then small ore pieces, slag fragments, and remains from furnace walls were discovered in shallow hollows or on the subsoil in this ironworks. The material described has a distinct magnetic reaction. The sample was marked as a material of technical rather than geological (Souchopová 1995, 46). These were the remains of iron ore prepared for smelting by crushing and roasting; the layers were for the most part situated near furnaces. We also did some simple experiments with roasting of ore that had been found and we discovered that the ore sample that had been exposed to weaker, unstable roasting best corresponded to the technical material described above. This corresponds best to ore roasting in heaps with free access of oxygen (Souchopová 1986, 65-66).

Another piece of information obtained by research on smelting remains in the ore-bearing central part of the Moravian Karst is determination of the sequence and time period of the different types of furnace that were used.

Both of the oldest ironworks from the end of the 8th and the beginning of the 9th centuries worked with the same furnace type, an underground furnace with a long frontal tunnel (the Želechovice type; Pleiner 1958, 220; 2000, 190–193). Furnaces were placed in rows next to each other with frontal openings facing the stream. The two bloomeries were situated only 140m from each other on the bank of the stream coming from the U kukačky spring. The ironworks area was kept clean, waste material being thrown down the slope towards the stream. Building furnaces in batteries made their handling easier. The excavation demonstrated that furnaces worked in rotation (e.g. only second ones were in operation at the same time) and this facilitated furnace repairs after smelting. The dating of the furnaces in the ironworks of the central part of the Moravian Karst and in the eponymous locality at Želechovice is, in principle, identical (Souchopová 1986, 15–23).

Another type of furnace found in the central part of the Moravian Karst is an embanked furnace with thin frontal wall discovered in a Great Moravian bloomery from the second half of the 9th century in the U obrázku forest section (Cad. of the village of Olomučany). They are also known after the eponymous Hungarian locality as the Imola type (Fig. 30: b). At the same time in this Great Moravian bloomery another type of furnace was in use. It was a type of standing shaft-furnace with a shallow hearth and a large gate panel (Nemesker type: Gömöri 2000, 242). Its typical feature is the shallow dish-shaped hearth and a large gate panel inserted into the frontal part of the furnace. The panel had a slot for

a bellows, and slag was tapped through a low part of the panel. Panels were probably only baked by the heat of the furnaces. Small fragments of them were found in slag heaps. They were strengthened by a coating of slag on the hot side. This type of panel was used for both types of furnace (Souchopová 1986, 28–31, fig. 4). Part of the slag from both types of furnace was also tapped out of the hearth. Evidence of it can be seen in fragments of fan-shaped tap slag from the debris.

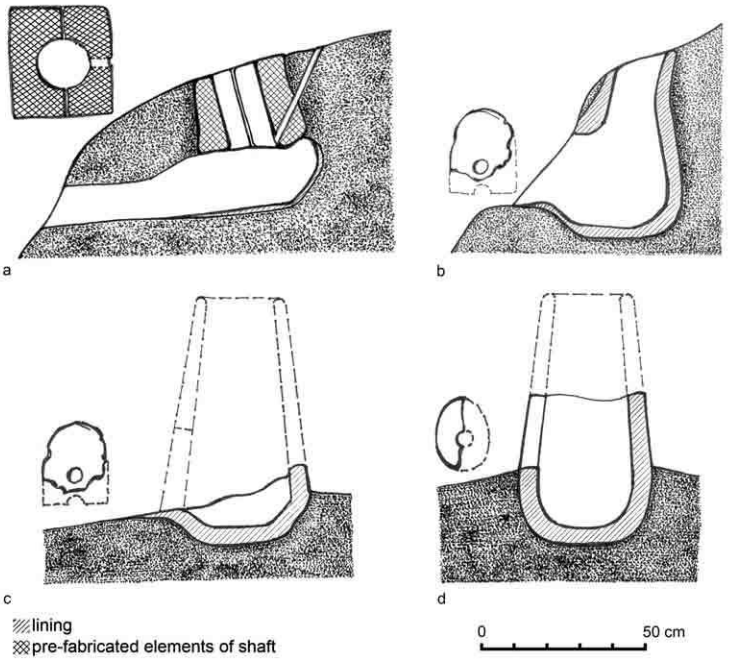

Figure 30: Cross–sections of furnaces found in bloomeries in the central part of the Moravian Karst: a. underground furnace with a long frontal tunnel; b. embanked furnace with thin frontal wall; c. free-standing shaft furnace with shallow hearth; d. slag-pit furnace. Drawing by J. Merta.

A further type of free-standing shaft-furnace was discovered in bloomeries in the central part of the Moravian Karst working in the end of the 10th and in the 11th century. They are free–standing pit slag furnaces. Typical examples come from the ironworks on Růžová street in the village of Olomučany (Cad. Nos. 951/2, 951/3; Souchopová 1986, 39–42). As the name implies, the furnace hearth was dug, in this case 35–50cm, below the subsoil level. Slag was concentrated in the hearth. We do not have any evidence of tap slag having solidified outside the furnace. Air blast was provided by bellows through a slot in an oval gate panel in the frontal part of the furnace (Fig. 30: d).

In the Great Moravian ironworks from the second half of the 9th century

(forest section 98/1, known as U obrázku, village of Olomučany) we tried to discover how much iron could be produced with ten furnaces. The bloomery was built on a platform set on a slope. The smelters threw waste beneath the low edge of the platform where the slag heaps, up to 9m wide and up to 0.9m high, still remain. With the help of calculations from the weight of the slag separated from a part of the heap under furnace IX, we were able to find out that 54–270kg of iron could be produced in this furnace; the average value is 162kg of iron. The bloomery production varied from 1620 kg to approximately 2700 kg of iron. We presume that the higher value, based on the experimental smelting in this type of furnace (Souchopová 1986, 31), is the more probable.

In larger-scale production, such as that evident in the Great Moravian ironworks, and also in ironworks with Želechovice-type furnaces, we must naturally consider the fact that there were many of other workmen besides the smelters. There were the miners who exploited iron ore and transported it to the bloomery, there were masters who worked on charcoal burning, and probably blacksmiths who cleaned and worked up the sponge iron into the quality and shape of iron blooms. It was also necessary to transport food to the central part of the Moravian Karst and to provide meals. Without a doubt, many of these activities blended together, but certainly in bloomeries, which had an intensive method of working, it is essential to consider the background of the needs for the operation of the bloomery. The transport of the iron to the place of its consumption obviously belongs in this category. There was no use for such a large amount of iron in the forests in the central part of the Moravian Karst, which was an uninhabited forested countryside during this period. Its only settlers were the miners and smelters themselves and those who worked in the background. It must therefore be kept in mind that the iron was transported to some settled territory, most probably through the fortified settlement of Staré zámky near Líšeň. It is assumed that this could operate as an 'iron castle' which was a place where iron dues (*tributum ferri*) were paid. This is indicated by ceramic finds from the bloomery in the Habrůvecká bučina forest section, which was working at the end of the 10th and in the 11th centuries (Merta 2000), and it corresponds exactly with ceramic finds from this fortified settlement. However, this is only a hypothesis based on the proximity of the fortified settlements, and the supposed organization of ironworks within the Great Moravian Empire. We base our knowledge on the general situation at the time and on Hungarian written sources in which iron castles (*castra ferrea*) are mentioned. These castles were presumably in operation in the 10th century – Vasvár iron castle is mentioned from 1108. Similar centralized organization was also achieved, for example, with salt ('Salt castle' = Austrian Salzburg;

Heckenast 1967, 60; Kučera 1984, 61–62).

This brings us to the question of the organization of work, not only in individual bloomeries, but in iron smelting as a whole in the central part of the Moravian Karst. So far we have supposed that the bloomeries that we know from the central part of the Moravian Karst from the end of the 8th and in the 9th centuries were characteristic of a larger craft community whose members performed these types of work. They would have been free individuals who were probably required to supply specified amounts of iron to the centres of the ruling country of the time (Pleiner 1958, 228: Souchopová 1986, 80–81). From a summary of the findings of archaeological excavations in the central part of the Moravian Karst, there is another possible interpretation, so far merely hypothetical, of the numerous workmen's groups that were responsible for this ironmaking. This postulates that there was long-term activity with intensive production, for which time considerable iron production was required for which it was necessary to organize it as an overall operation. In the light of existing knowledge derived from archaeological excavation, it appears as if this production was not only connected to some of the centres of that time, but was also probably centrally organized (Souchopová & Stránský 2008, 116). This highly specialized production was situated far from fortified settlement, but it could be carried out by workmen ranking among family (*familia*), i.e. notable representatives of that society (Charvát 1985, 181). The connection to Moravian fortified settlements of that period is illustrated by ceramics discovered in the central part of the Moravian Karst in bloomeries and their analogy with findings from South Moravia (Blučina, Lanžhot; Souchopová 1986, 19).

Looking at the hypotheses regarding the social classification of smelters in these types of ironworks, there could also be a connection with the fact that the same types of ironworks and furnaces are situated in both the central part of Moravian Karst and the village of Želechovice near Uničov. The Želechovice bloomery was founded in the area which, it is assumed, was influenced by the expansion of a Low Moravian duke around the year 800. A fortified settlement situated in what is now Olomouc was violently destroyed in this time. It is assumed that one particular cause for stress in the north could have been increasing iron consumption. This fortified settlement in Olomouc was situated on the way to the iron-ore bearing area of North Moravia. The ideas based on the findings from new archaeological excavations range from one hypothesis to another, but it currently seems that a magnate who was a part of the political structure of the old Moravian state reigned at the settlement in Olomouc in the second quarter of the 9th century at the latest (Michna & Pojsl 1988, 30). The discovery of iron-production sites where only one type of furnace

and working methods were in use point to the possibility that a group of specialist ironmasters developed who utilized a single furnace type with appropriate production techniques. On the basis of the evaluation of the work of the Želechovice bloomery, R. Pleiner already drew attention to the fact that ironworks of this type often have an image of the manufacture (1958, 228).

In support of the hypothesis about centrally controlled iron production in the central part of the Moravian Karst, we can look at the findings of embanked furnaces with thin frontal walls (the Imola type). They were discovered in the intensive working Great Moravian bloomery mentioned above (forest section 98/1, U obrázku, Cad. of the village of Olomučany). From the 9th century this type of furnace is known only from the central part of the Moravian Karst, but in later centuries there were many of these furnaces. They appeared in bloomeries in northern and western Hungary, north-eastern Austria, and southern Slovakia, but also, for example, in Praha–Košíře–Kotlářka or in Kuřim near Brno (Souchopová 1995, 20–26). In Hungarian literature this type of furnace is defined as a type representing the early royal organization of iron manufacturing ('This type is considered to represent the royal iron producing organization,' Gömöri 1989, 130). If we take another look at this, we can accept it as a really significant hypothesis. These furnaces, which operated in Moravia during the blossoming of the Great Moravian Empire in the 9th century, appeared after its fall in the places where centres of new states were rising, namely in Hungary and Bohemia. The decline of this productive type of iron making in the central part of the Moravian Karst, and mainly the later bloomeries with this type of furnace, can be related to the development of the so–called 'servant organizations' described in later written sources.

Differentiation in various branches of craft manufacturing is already sufficiently proven through archaeological excavations, which means that we can diagnose distinct differences between craft manufacturing in villages settlements and those which were concentrated in the Great Moravian centres (Měřínský 1983, 42–45). In this respect, we must say that centrally organized iron smelting in the central part of the Moravian Karst more likely corresponds with the specialized manufacture associated with the Great Moravian centres by its intensive manufacturing character, its size, and the productivity of its labour. This ironmaking had to accept only one thing: the natural resources needed for iron smelting are situated outside ordinarily settlements.

Another piece of knowledge that is helping to support the hypothesis about the central regulation of Great Moravian iron smelting in the central part of the Moravian Karst is the discovery of a certain hiatus in the

Figure 31: Reconstruction of the original view of the Great Moravian bloomery (9th century), Olomučany, forest section 98/1, central part of the Moravian Karst. Drawing by J. Balák. After Souchopová & Stránský 2008.

building of bloomeries, which started at the beginning of the 10th century and persisted at least for half or three-quarters of a century. This was probably due to the general situation of the country following the fall of the Great Moravian Empire. The disintegration of its social and economic structure and the arrival of centralized power in Bohemia and in the territory of the Arpad state probably brought about the end of iron smelting of the Great Moravian type in the central part of the Moravian Karst. The period of large, intensively working bloomeries came to an end there

(Souchopová 1992, 133-134).

The working system in the smaller bloomeries that were set up in the Moravian Karst at the end of the 10th century was different from the work organization in the Great Moravian period. These bloomeries did not conform with the traditions of Great Moravian iron smelting, and they also used another type of furnace. These ironworks had a limited capacity for production and obviously fewer workmen. They were probably members of the smelters' families, in this case more likely blacksmiths who came to the central part of the Moravian Karst to produce iron only for the needs of their smithies.

References

Charvát, P. 1985, 'Zpracování železa v písemných pramenech českého středověku do počátku 14. století (s přihlédnutím k výzkumu v Chýnici)', 'The metallurgy of iron in the written sources of medieval Bohemia to the beginning of 14th century (in connection with the results of excavations at Chýnice)', *Archeologické rozhledy* 37 (2), 181–185.

Gömöri, J. 1989. 'The Hungarian Bloomeries', in R. Pleiner (ed.) *Archaeometallurgy of Iron 1967–1987* (Praha), 125–138.

Gömöri, J. 2000, *Az avar kori és Árpád-kori vaskohászat régészeti emlékei Pannoniában: Magyarország iparrégészeti lelőhelykatasztere I. Vasművesség* (Sopron).

Heckenast, G. 1967, 'Eisenverhüttung im Burgenland und Westungarn im 10. bis 13. Jahrhundert', *Burgenländische Heimatblätter* 29/2, 55–65.

Kreps, M. & Merta, J. 1973, *Stará huť u Adamova. Státní technická rezervace*. Účelový výtisk Technického muzea v Brně.

Kučera, M. 1984, 'Hutnictví železa na Slovensku v 10.–13. století', in R. Pleiner, J. Kořan, M. Kučera, J. Vozár, *Dějiny hutnictví železa v Československu 1: Od nejstarších dob do průmyslové revoluce* (Praha), 59–65.

Měřínský, Z. 1983, 'K problematice archeologického výzkumu řemeslné výroby 10.– až první poloviny 16. století na Moravě a ve Slezsku'. ‚Zur Problematik archäologischer Untersuchungen der handwerklichen Produktion vom 10. bis die erste Hälfte 16. Jahrhunderts in Mähren und Schlesien', *Archeologia Historica* 8, 41–71.

Merta, D. & Merta, J. 2000, 'Archeologický výzkum raně středověké železářské huti v Habrůvecké bučině', *Archeologia technica* 11, 33–42.

Michna, O. & Pojsl, M. 1988, *Románský palác na olomouckém hradě. Der romanische Palast auf der Ölmützer Burg* (Brno: Muzejní a vlastivědná společnost v Brně).

Pleiner, R. 1958, *Základy slovanského železářského hutnictví v českých zemích* (Praha).

Pleiner, R. 2000, *Iron in Archaeology. The Early European Bloomery Smelters* (Praha).

Souchopová, V. & Stránský, K. 1989, 'Experimental Iron Smelting in the Blansko Region, Czechoslovakia', *Archaeomaterials* 3 (2), 149–161.

Souchopová, V. & Stránský, K. 2008, *Tajemství dávného železa. Archeometalurgie objektivem mikroskopu. Secret of early Iron. The Archaeometallurgy under the Microscope* (Brno: Studie z historie techniky a průmyslu 2).

Souchopová, V. 1970, 'Výsledky výzkumu hutnické dílny v Padouchově u Josefova', in *Sborník Okresního vlastivědného muzea v Blansku* 2 (Blansko), 15–26.

Souchopová, V. 1986, *Hutnictví železa v 8.–11. století na západní Moravě. Die Eisenverhüttung des 8.– 11.Jh. in Westmähren* (Brno: Studie Archeologického ústavu ČSAV v Brně XIII/1).

Souchopová, V. 1992, 'The Main Tendencies of Development of West Slav Iron Metallurgy from its Origin until the 11th century', in *Medieval Europe* 1992, vol. Technology and Innovation (York), 131–136.

Souchopová, V. 1995, *Počátky západoslovanského hutnictví železa ve světle pramenů z Moravy. The Beginning of the Metallurgy of Iron among Western Slavs in the Light of Sources from Moravia* (Brno: Studie Archeologického ústavu AV ČR Brno XV/1).

Norway as a bloomery iron producer

A. Espelund

Archaeometallurgical studies of bloomery sites in Norway since about 1982, greatly aided by the 14C-method, have led to a new picture of this activity. A large shaft furnace with a slag pit was in use from about 300 BCE to 600 AD, the smaller shaft furnace with side tapping from about 700–1300, and the most recent – a dug-in furnace with no tapping of slag– from 1400 to 1800. The use of induced draft during the first period created by direct insertion of wood and a transformation to charcoal in the furnace represents a striking alternative to the conventional picture of an operation requiring charcoal and bellows. The changes of technology some time between 600 and 800 as well as around 1300-1400 raise challenging questions. The author is heavily involved in a study of the carbon control in all three types of processes, not to be dealt with in the present paper. They can tentatively be classified by volume-zone control, a two-step process and time control.

Mid-Norway - Metallurgy - Bloomery ironmaking - Three periods - Slag control

Introduction

Three major impulses have given impetus to the study of early ironmaking in Norway:

a) the introduction of the radiocarbon (14C) method for dating of both charcoal from slag heaps and also objects of iron and steel containing a minimum of carbon.

b) the lasting inspiration to the study of the archaeometallurgy of iron by Radomír Pleiner and his group in the Comité pour la sidérurgie ancienne.

c) the involvement of extractive metallurgy with roots in physical chemistry as a supplement to archaeology, for both laboratory studies and process analysis.

In Norway bloomery iron was made from bog iron ore during three periods with booms around the years 200, 1100, and 1600. Each period is characterized by a specific type of process, documented by furnace remains,

typical slag, and also a certain context. For the furnaces there is also a noticeable regional distribution. As a majority of the sites are found at altitudes above the permanent settlements, not far below the tree-line, most sites have not been affected by cultivation. They seem to number some 10,000. In this paper only a few highlights can be presented.

A. Archaeology

1. In 1982 the archaeologists at the University in Trondheim were introduced to the bloomery site at Heglesvollen in North Trøndelag. It consisted of four furnaces regularly positioned 6m apart along a terrace facing the course of an old river. Research excavations in the years that followed showed that the slag heaps were equally large with a total of some 96 tonne, suggesting that the furnaces had been operated at the same time by a crew, assumed to consist of about ten people (Farbregd *et al.* 1985).

It soon became clear that the furnaces had been constructed with a clay shaft above ground and a well preserved dug-in stone-lined slag pit containing up to 150kg of slag. The slag pits, which measured *c* 80cm in diameter and in depth, were equipped with a vertical slot *c* 40cm wide, allowing for the removal of solidified slag. The produced blooms at the end of a smelting run were probably removed in the red-hot state through this opening. It appears that they numbered five, each weighing *c* 18kg. One excavated furnace is shown in Pleiner 2000, pl. XI (see also Espelund 1996).

There is a strong indication that the furnaces were operated at two different temperature levels. Reduction took place at a moderate temperature. Split pine was introduced in the shaft whenever tapping of slag (and also sintering of the bloom) were aimed at. The combustion of tar and resin on top created a chimney effect, which led to a temperature increase in the zone around the air inlets just above the ground level where charcoal from the previous charge of wood was present. No bellows were needed.

This type of site is invariably sited at the edge of terraces, facing water: a lake, a river, or just a small creek. The function of the water has not been explained. Since 1982 some 300 sites of this kind have been registered in Trøndelag, with sets of furnaces numbering from three to eight. More than fifty sites have been ^{14}C-dated, representing the period from about 300 BCE to AD 600 (Stenvik 2005,114). The earliest dates are a little uncertain because old and dry pine could be used as fuel.

At two sites out of ten house-sites have been partly excavated, leading to the illustration, shown in Fig. 32 /Plate XII/. However, the lack of finds

representing the presence of human beings rules out the idea of quarters for the workers and their families; nor had they been used as byres. The houses have had some other function, perhaps as carpenters' shops. The height near the tree-line indicates iron smelting during the summer months only and the use of tents as quarters.

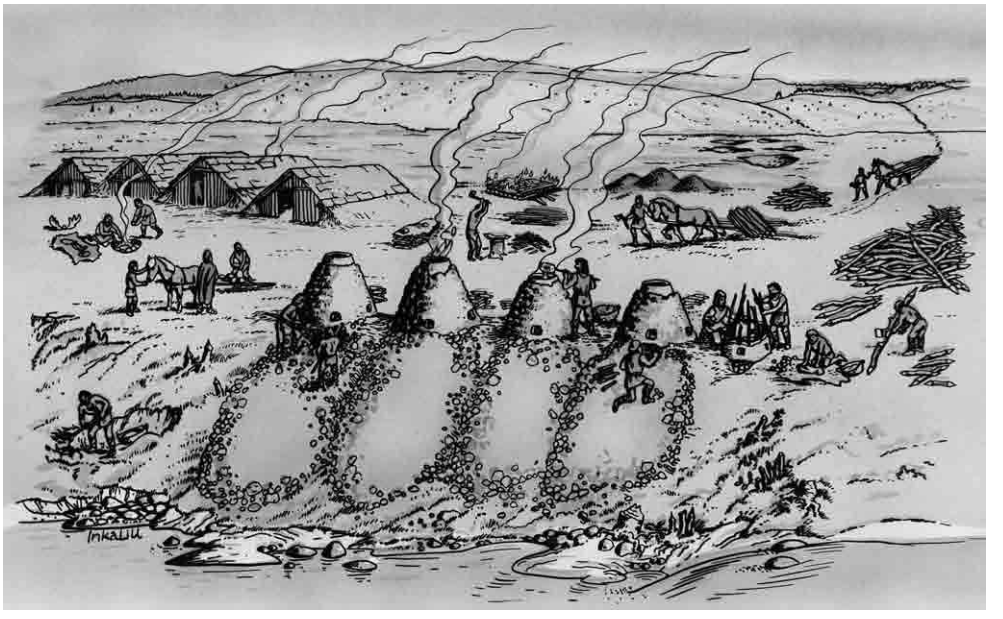

Figure 32: Drawing from 1991 of a Roman age bloomery in Trøndelag by Inkalill, slightly revised later by the designer. Notice the cyclic operation of the four furnaces.

The operation of the bloomery sites during this period gives the impression of an industrial activity, with specialization, crews of about ten workers, an infrastructure for the supply of food, and perhaps even shift working.

It is remarkable that the iron workers were taken out of agriculture during the summer months. This indicates that the local population was larger than hitherto assumed. These specialists probably were searching for and digging ore during the autumn and spring. In winter they transported wood to the bloomery sites. The blooms produced were taken to the nearest community or harbour. A study of a smithy from the same period in the community of Singsås in Midtre Gauldal has recently been initiated (Øien, R.I. 2009. Personal communication).

The total annual production in Trøndelag around AD 200 may have been some 40 tonnes, corresponding to 4000 axes. A considerable amount of export must have taken place. The sites of boat sheds measuring *c* 15m long have been found at 10–15m a.s.l., equivalent to the land rise over two millennia. It is therefore likely that iron produced in Trøndelag was

exported by sea to North Norway, and also to the Continent or to the British Isles.

The standard products during this period were blooms, weighing *c* 18kg. Metallographic studies have shown that the blooms were of an excellent quality when taken out of the furnaces: slag-free, low in detrimental P and S, with carbon contents between 0 and 0.7%. A low density (around 6) shows that they contain a number of small pores, evenly distributed. Such a bloom, radiocarbon-dated to the beginning of the Iron Age (500 BCE) is shown in Fig. 33 /Plate XII/: note the deep cut, made immediately in the red-hot state with an axe without any reheating.

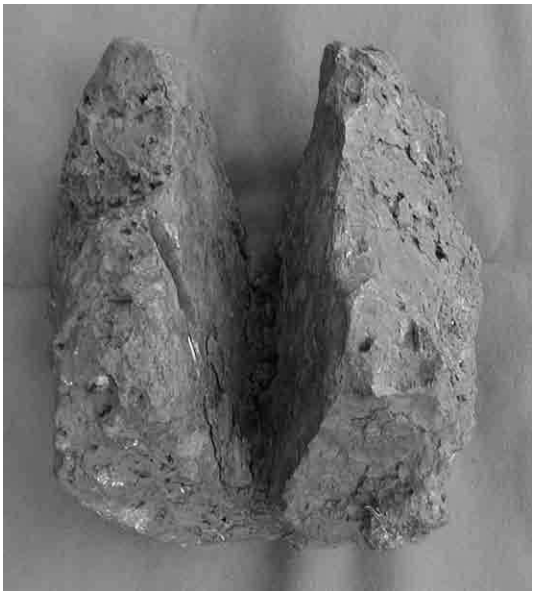

Figure 33: Bloom from Akset containing about 0.2% C. Weight 17.8kg. T - 21 175. Photograph by A. Espelund.

The Heglesvollen type of furnace is found also in neighbouring Jämtland in Sweden, where it is described as 'shore-bound'. A type of shaft furnace with slag pit is also found in the Østland area: however, most of them are different in size, not in groups, and not necessarily located next to a source of water.

The finds of Roman Age type furnaces led to the conference in Budalen 1991 entitled 'Bloomery ironmaking during 2000 years,' which was attended by around 120 participants from sixteen countries, including Radomír Pleiner. The organization of the conference was coordinated with the Ancient Ironmaking Committee.

Shaft furnaces with slag pits are also known on the European continent. However, the specific form of operation, without any need for bellows and with the re-use of the furnace after removal of the slag, seems to be specific

for Trøndelag and the neighbouring area in Sweden.

The discovery of the Roman age and newer furnaces led to the establishment of the 'genealogical chart' in Fig. 34, first presented in 1992 (Espelund). During subsequent years the only major modification related to a prolongation of Period II in certain areas.

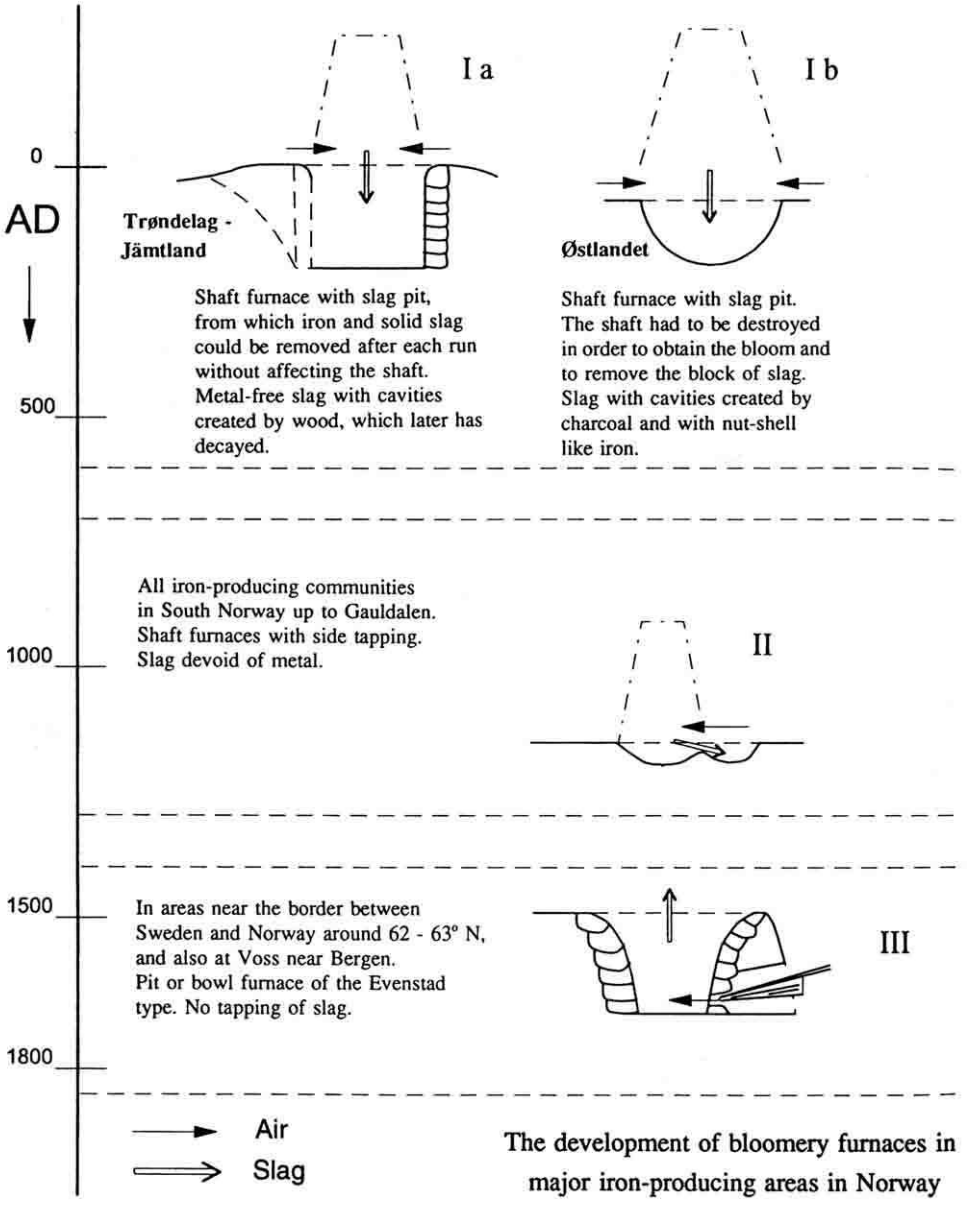
0
AD
500
1000
1500
1800
I a
I b
Trøndelag -
Jämtland
Østlandet
Shaft furnace with slag pit, from which iron and solid slag could be removed after each run without affecting the shaft. Metal-free slag with cavities created by wood, which later has decayed.
Shaft furnace with slag pit. The shaft had to be destroyed in order to obtain the bloom and to remove the block of slag. Slag with cavities created by charcoal and with nut-shell like iron.
All iron-producing communities in South Norway up to Gauldalen. Shaft furnaces with side tapping. Slag devoid of metal.
II
In areas near the border between Sweden and Norway around 62 - 63° N, and also at Voss near Bergen. Pit or bowl furnace of the Evenstad type. No tapping of slag.
III
Air
Slag
The development of bloomery furnaces in major iron-producing areas in Norway

Figure 34: The types of representative furnaces and their distribution in time (Espelund 1992).

2. Around 800 a new and smaller type of furnace was introduced in

Norway. It is a clay shaft furnace with side tapping of slag, of a type that is known from a wide area. The inside of the shaft was cylindrical, making it possible to remove the hot bloom upwards. The furnace was charged with charcoal and roasted ore, and the furnaces were operated with bellows. Charcoal was made in pits measuring c 2–8m in diameter, mostly situated near the furnaces and therefore probably operated in connection with the smelting. Charcoal from both pine, spruce, and birch seems to have been used for the smelting, depending on whatever was available. The best preserved known furnace from this period is shown in Fig. 35 /Plate XIII/.

Figure 35: Furnace excavated at Dokkfløy. It was built from clay and was supported by vertical slabs on three sides. Note the hole for the nozzle of a bellows and for tapping of slag in front. Photograph by M. Thorleifsen.

Most of the slag heaps from Period II are found in the Østland area. Major excavations have been led by the archaeologists Jan Henning Larsen, Lars Erik Narmo, and Bernt Rundberget (Larsen 1991; Narmo 1997; Rundberget 2007). The slag heaps contain from about one to twenty tonnes. Some 100 sites have been registered located in many communities, leading to a careful evaluation of some 10,000 furnaces.

The standard product of this period was a split bloom, weighing from 5kg to 12kg. Here again the metal is of excellent quality – slag-free and low in sulphur and phosphorus. The blacksmiths said of the blooms that “they

were flowing on the anvil". Twenty such blooms in the Museum of Cultural History in Oslo have been studied by Martens (1979). The big surprise is that nearly all stem from the county of Telemark. This is systematic, not only the result of the search. A bloom from Veum is shown in Fig. 36 /Plate XIII/.

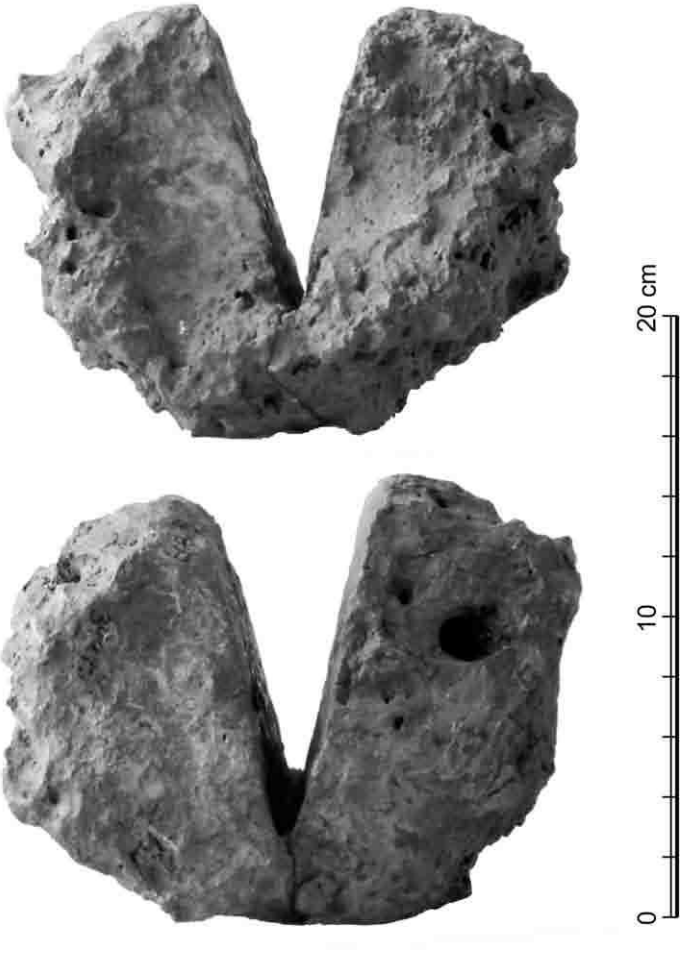

Figure 36: Bloom from Veum, Fyresdal, County of Telemark. Photograph by KHM.

At most places in Norway the 'medieval' process (No. II) went into oblivion at the Black Death, which struck the country in 1349. However, in Fyresdal (Telemark) this author has found slag heaps representing ironmaking with this process dating up to 1500. They are invariably found at about 300m a.s.l., whereas ironmaking during the Early Middle Ages took place at farms situated around 60–700m a.s.l. When farmland became available as a result of the plague, the farms at high altitudes were deserted and the skilled ironmakers moved to empty farms down in the

valley, where they found bog ore. This pattern has been confirmed by means of radiocarbon-dating of charcoal from slag heaps. For a short period they produced some metal, in an area in which cereals had previous been produced (Espelund 2004a).

3. In East Norway at around 63 °N a third process was established around 1400. It was described by the author Ole Evenstad in a book from 1790, which was awarded a gold medal by the Royal Agricultural Society in Copenhagen. It was also translated *in extenso* into German in 1801 (Evenstad/Blumhof 1801), and a short English version was published in 1968 (Evenstad/Jensen 1968). The manuscript from 1782 has led to successful re-enacting of the process. As a contemporary document it is remarkable, comparable only with descriptions of the Catalan process in Catalunya and the Basque area.

B. Metallurgy

1. The involvement of metallurgy has led to revised figures for outputs, and above all an emphasis of the significant properties of slag, found at bloomery sites. A shift from morphology alone to include process analysis has also taken place.

Successful smelting during all three periods led to slag analyses with about ± 25% SiO_2. The individual values for FeO and MnO vary greatly. Because of similar properties as constituents of a slag, they may be added together, leading to a constant sum of 62 ± 3% for FeO + MnO. According to the phase diagram FeO-(MnO)-SiO_2, such slags are fluid around 1200 °C or even lower, owing to minor amounts of other oxides.

English-speaking metallurgists have created the expression '*Make your slag and the metal looks after itself.*' According to the Fe–C equilibrium diagram, a carbon content of 2% can be expected in iron created at 1100 °C in the presence of burning charcoal and a gas composed of mainly CO and N_2. A high activity of FeO (in a chemical sense) is therefore required for the lowering of the carbon content to acceptable values in the range 0–0.8% C. The carbon content is evidently governed by the chemical equilibrium

$$FeO + \underline{C} \rightarrow \mathbf{Fe} + \mathbf{CO}$$

in which $\underline{C}$ represents carbon dissolved in solid iron. The analytical values quoted represent slags with a chemical activity of FeO near 1. This desired mechanism is known as 'slag control'. The present author presented a full account of slag control in the Roman Age furnace at the conference in Bradford, 2009 (Espelund 2009).

2. The remaining question is how the ideal slag can be created. There is a tendency in a simple bloomery process to over-reduce the iron oxide

in roasted bog iron ore to metal, without securing the right type of slag. It requires a reaction between intermediate FeO and SiO_2.

Recent finds, reminiscent of normal slag, but with a content of only some 7–9% SiO_2, indicate either unsuccessful smelting or 'something else'. Small amounts of slag with this low content have been found at five sites, sometimes together with large amounts of normal 'end' slag with *c* 23% silica. This has led to the suggestion by the present author that successful ironmaking might consist of two steps: the first is pre-reduction with slag formation leading to a semiproduct composed of free FeO and iron silicate Fe_2SiO_4, which was then smelted in a second phase to iron and normal 'end' slag. This has been presented to an international audience (Espelund 2007).

A micrograph of such slag found at the site Nystaul in Vinje, Telemark is shown in Fig. 37.

This might give an answer to the function of the *hellegryte*, an enigmatic find at Møsstrond in Telemark from about 550–700 (Martens 1988). It may also explain the superb quality of ancient blooms in the Museum of National Antiquities in Oslo (Martens 1979; Espelund 1998-1999).

Needless to say, this pretreatment represents a very interesting and metallurgically sound solution to the problem slag formation. However, how this step No. 1 was performed is still a question.

3. The outcome of modern practical experiments does not seem to match the quality of ancient blooms nor the output of iron, relative to the amount of slag. The output of iron can be as high as 1.5 : 1 relative to the weight of slag, as presented by the present author (Espelund 2004b), while a ratio of 1 : 1 seems to be more normal. These figures stem from finds of slag together with representative ore, determined by following the elements Fe, Si, Mn, and Al from ore to metal and slag.

4. Slags representing a possible pretreatment seem to be documented to the period from about 500 to the Merovingian era. However, it is possible that such pretreatment after 800 was achieved in the characteristic medieval furnace and therefore left few traces. The great change in technology some time between 600 and 800 therefore may even express the advent of a furnace which lent itself to both processes. Another reason for abandoning the large furnace type of the Early Iron Age followed by a possible hiatus might be the loss of the market for iron in continental Europe. It is even possible that iron production stopped completely around 700, before the new technology was introduced.

5. The suggested two-step process represents a major achievement by our forefathers. It could only be revealed by the use of analytical data, and also the type of questions raised from the point of view of physical chemistry. This approach has to start with the equilibrium aspects, such

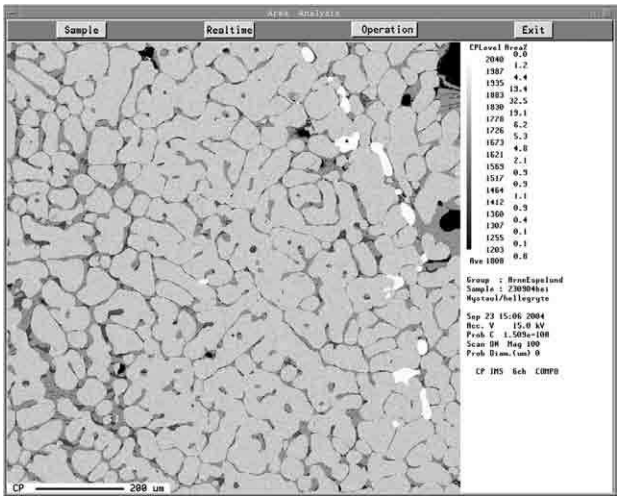

Figure 37: Micrograph of slag from Nystaul NIKU 99/31 in Vinje. White specks are iron, grey rounded particles are FeO, matrix slag. Metallography by M. Raaness. Chemical analysis in the table below:

	FeO	MnO	$PSiO_2$	Al_2O_3	P_2O	Sum of 10 oxides*	FeO + MnO	• R
Hellegryte slag	90.5	0.25	6.33	0.63	0.138	98.27	90.75	11.95

* CaO, MgO, TiO_2, BaO, K_2O all below 1%

as those expressed by the iron–carbon diagram, the equilibria involving the gas mixture, and the relation between the metal and the slag. The slag is a very important partner in the whole process, demonstrating both the raw material and the quality of the resulting metal.

The outcome is remarkable as it leads to a revised organizational pattern at the bloomery sites, meeting important questions of archaeologists and also experimental blacksmith.

The present author fully agrees with the following statement by Radomír Pleiner that 'It is well known that the bloomery process produces iron which is usually low in carbon or heterogeneously carburized, but he equally fully disagrees with his explanation that 'This is due to the fact that the carbon absorbed by the iron during reduction is completely or partially oxidized by the air flow at the tuyère level of the furnace' (Pleiner 2000, 13). Why, then, did no refining take place in the blast furnace? Why is the analysis of slag so uniform across the furnace and not dependent on the distance from the tuyère?

By implementing chemical analysis and some physical chemistry, in addition to good archaeology, the archaeometallurgy of iron will receive a new impetus. It is my hope that I can contribute to this development, in

spite of my advanced years. As to age I am following in the footsteps of Radomír.

Concluding remarks

Norway is at the tail end of Europe. My country is not known as a large producer of iron. However, probably no other country in Europe can offer such a large number of undisturbed slag heaps, representing at least three different types of furnaces/processes over a period of nearly 2000 years. They are situated in landscapes of widely varying character with respect to availability of wood, precipitation, height above sea level, geology, and habitat. Each type of process seems to be of a very specific and uniform character.

The present author will not demand that the results of investigations in his home country should be projected on to the bloomery ironmaking of continental Europe. At best the finds in Norway can represent a sort of 'bank' for the study of furnaces, types of slag, and blooms. It is also my hope that our research will meet an international standard.

It is deplorable that I have only met Radomír a few times. At late hours in conferences I discovered that we share an interest for singing. I am sure that we would have developed a good common repertoire of songs in many languages if we had had an opportunity to meet more frequently.

References

Espelund, A. 1992, 'Ole Evenstad - liv og virke. Den yngre jernvinna i deler av Norge og Sverige', *Kilder - historie - metallurgi - funn m.m.* (Trondheim).

Espelund, A. 1996, 'The Trøndelag Bloomery Furnace – its operation and metallurgy revealed', in G. Magnusson (ed.), *The Importance of Ironmaking II* (Stockholm).

Espelund, A. 1998-99: 'Luppenstudien in Norwegen. I '..und sie formten das Eisen.'' *Archaeologica austriaca* 82-83 (Wien).

Espelund, A. 2004a, 'Jernet i Vest-Telemark. (With summaries in English)', *Arketype forlag* (Trondheim).

Espelund, A. 2004b, 'Utbytteberegninger ved jernvinneanlegg', in G. Guðmundsson (ed.), *Current Issues in Nordic Archaeology* (Reyk-

javik: Society of Icelandic Archaeologists).

Espelund, A. 2007, 'Direct ironmaking with partial reduction and slag formation as a first step', in *Proceedings of 2nd International Conference, Archeometallurgy in Europe*, 17-21 June 2007. CD-ROM. (Aquileia, AIM.)

Espelund, A. 2009, 'Bloomery ironmaking during the Roman iron age in Mid-Norway'. Presented in Bradford 2009.

Evenstad, O. 1790, *Afhandling om Jern-Malm, som findes i Myrer og Moradser i Norge, og Omgangsmaaden med at forvandle den til Jern og Staal* (København).

Evenstad/Blumhof 1801: Evenstad, O. 1801. *Praktische Abhandlung von den Sumpf- und Morast-Eisensteinen in Norwegen und von der Methode solche in so genannten Bauer-oder Blaseöfen in Eisen und Stahl zu verwandeln* [Aus dem Dänischen übersetzt und mit Anmerkungen begleitet von Joh. Georg Lud. Blumhof] (Göttingen: Dieterich).

Evenstad/Jensen 1968: Evenstad, O. 1968, 'A treatise on iron ore, as found in the bogs and swamps in Norway and the process of turning it into iron and steel' [Translation from Danish of chapters 1 – 9 by Niels L. Jensen], *Bull. Historical Metallurgy* Group 2(2), 61-65.

Farbregd, O., Gustafson, L. & Stenvik, L.F. 1985, 'Tidlig jernproduksjion i Trøndelag', *Viking* (Oslo).

Larsen, J.H. 1991, 'Jernvinna ved Dokkfløyvatn. De arkeologiske undersøkelsene 1986-89', *Varia* 23 (Oslo: Museum of Cultural History)

Martens, I. 1979, *Blåsterjern og fellujern. Noen synspunkter på en lite påaktet funngruppe* (Oslo: *Universitetets Oldsaksamling 150 år*).

Martens, I. 1988, *Jernvinna på Møsstrond i Telemark. En studie i teknikk, bosetning og økonomi* (Oslo: Norske oldfunn XIII).

Narmo, L.E. 1997, 'Jernvinne, smie og kullproduksjon i Østerdalen. Arkeologiske undersøkelser på Rødsmoen i Åmot 1994 – 1996'. *Varia* 43 (Oslo: Museum of Cultural History).

Pleiner, R. 2000, *Iron in Archaeology. The European Bloomery Smelters* (Praha).

Rundberget, B. 2007, 'Jernvinna i Gråfjellområdet', *Varia* 63 (Oslo: Museum of Cultural history)

Stenvik, L.F. 2005, In *Trøndelags historie I* (Trondheim).

Examples of research on ancient and early European iron forging

The chemical and metallographic analyses of the prehistoric ring from the 'Bull's Rock' cave
by K. Stránský

The craft of the Dacian blacksmiths
by Ľ. Mihok and V. G. Kotigoroshko

Early medieval knife manufacture in Britain; a comparison between rural and urban settlements (AD 400–1000)
by E. Blakelock and G. McDonnell

Metallography of knives from the medieval village of Hrdlovka and the burial ground of Zlončice, Bohemia
by J. Hošek and P. Meduna

Technological traditions in the craft of the blacksmith in old Russian Shestovitsa
by G.A. Voznesenskaya

Further metallographic studies on early armour from Churburg
by A. Williams

From Soissons to Beauvais: the use of iron in some French cathedrals
by P. Dillmann

The chemical and metallographic analyses of the prehistoric ring from the 'Bull's Rock' cave

K. Stránský

The paper presents the results of the metallographic and X–ray VD electron microprobe chemical analyses of the prehistoric hollow ring from the Bull's Rock (Býčí skála) cave. This Hallstatt hollow ring is dated to 600–500 BCE. The analyses resulted in the following conclusion: in the structure of a ring fragment, mostly of iron oxides, small quantity of copper oxides and traces of metallic copper and tin were found. The Hallstatt ring from the Bull's Rock cave was most probably forged of steel with a low carbon content. It was not either grey or white cast iron.

Bull's Rock cave - Hallstatt prehistoric ring - Electron microprobe analyses - Metallographic analyses - Iron and cooper oxides

Introduction

The ground plan of the Bull's Rock cave is shown schematically in Fig. 38. The hollow ring from the cave is shown in Fig. 39 /Plate XIV/; its external diameter is 43mm, internal diameter *c* 20mm, and wall thickness less than 2mm. The weight of the ring is 22g and its density is 6.98g/cm^3 (Absolon 1970, 215).

The prehistoric ring has an attractive modern history. It was discovered by a Moravian archaeologist, medical doctor H. Wankel, in a Hallstatt forging shop in the Bull's Rock cave (Fig. 38) situated near the little town of Adamov in 1872. Dr Wankel assumed this ring to be made of grey or white cast iron and considered it to be the oldest iron casting in the world. This interpretation of the origin of the ring was not shared by most European metallurgists, who were Germans. An archaeologist, Professor K. Absolon, the grandson of Dr. Wankel, interpreted the production of the prehistoric ring as a foundry technology.

After World War I a prominent metallurgist, Professor V. Jareš, used metallographic analysis in 1919 to ascertain the structure of the ring (Jareš & Absolon 1919). It is remarkable, that he considered the microstructure of the ring to correspond with that of forged iron. After the World War II

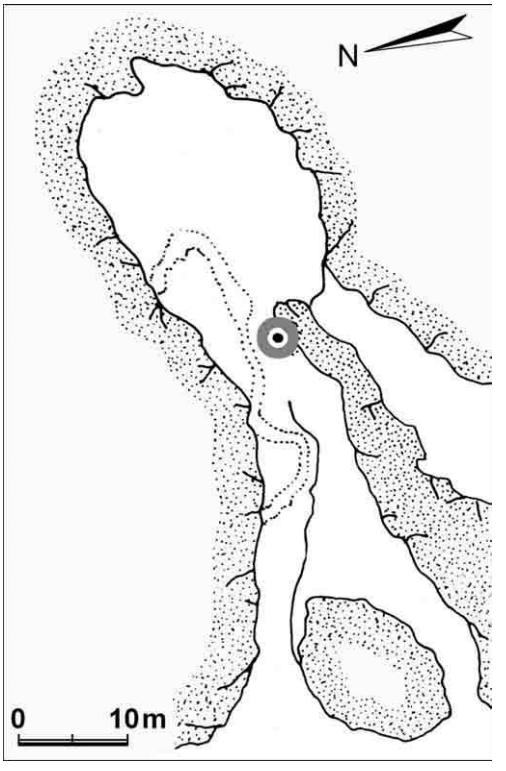

Figure 38: Ground plan of the entrance to the cave of Bull's Rock in the central part of the Moravian Karst. The black point indicates the probable location of the Hallstatt forging shop.

Professor Absolon published two articles in the *Illustrated London News*, in which he repeated his theory of the origin of the prehistoric ring from Bull's Rock cave (Absolon 1946). Another metallurgist, Professor F. Píšek, responded to these articles in a Czech journal *Hutnické listy* (Píšek 1947) and requested Professor Absolon to lend the prehistoric ring for a modern material analysis, but this request was turned down. Professor Píšek's request was accepted after the death of Professor Absolon in 1960 when his widow, Mrs. V. Absolon, agreed to new analyses of the ring. The analyses of chemical composition, metallographic structures, and phase composition were carried out in the laboratories of the Brno Military Academy and the Brno Technical University and were finished just after Professor Píšek's death at the beginning of 1970. The results were published as a short report in the Czech foundry journal *Slévárenství* (Stránský *et al.* 1973).

The present paper offers a short extract of the main results published by Stránský *et al.* (1973) and can serve as proof that the prehistoric ring from the Bull's Rock cave has kept its mystery until today.

Analyses

For the material analyses of the ring a 5mm - 7mm fragment was cut (Fig. 39: top right – location – a – and the detail in Fig. 39: bottom right /Plate XIV/) and prepared as a metallographic specimen perpendicularly to the wall of the ring (Fig. 39: bottom right – cut BB)). For the analyses the following methods were applied: X–ray wave dispersion spectral analysis (electron probe micro analyzer JEOL – JXA 3A) to determine the chemical composition and the metallographic observation (light microscope Zeiss Neophot II) to evaluate the microstructure.

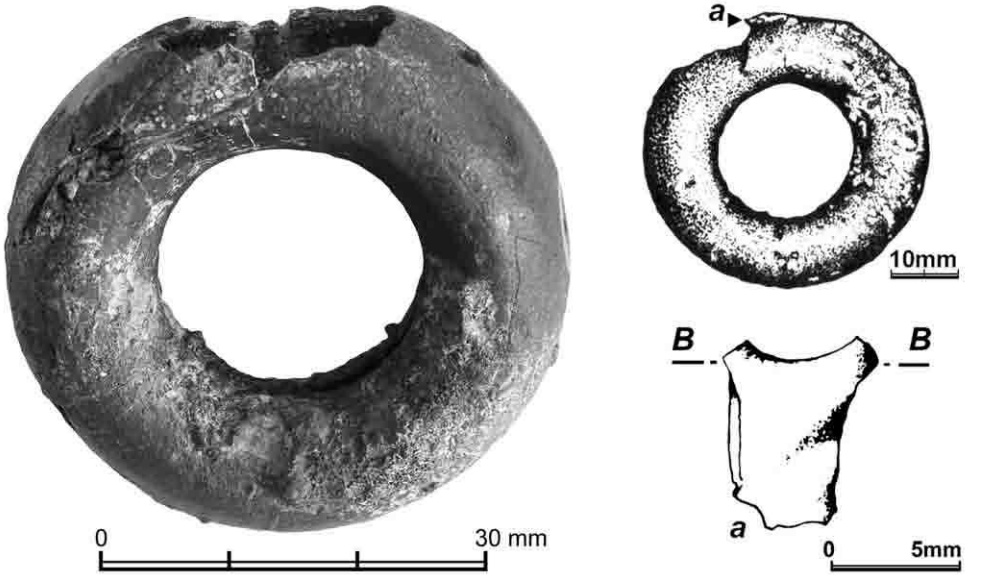

Figure 39: (Left) Photograph of the hollow ring from the Bull's Rock cave (collections of the Moravian Museum in Brno): (right) drawing showing location of (above) sample *a* taken from the ring and (below) cross-section B-B of the metallographic specimen. Photograph by I. Balák.

The structure of the cross-section of the prehistoric ring is shown in Fig. 40. The high porosity of the ring and the morphology of its structure, which are typical for the forged structures, can be seen. The results of more detailed structural and chemical analysis are in Table 1 and in Fig. 41 /Plate XIV/. In the structure of the ring it was possible to distinguish four structural components:

- The light–gray oxides consisting of 62.5 wt-% Fe, 36.0 wt-% O, and 0.3 wt-% C (the chemical composition probably corresponds to the mineral goethite FeO(OH));
- The gray oxides consisting of 65.3 wt-% Fe, 32.8 wt-% O, and 0.3

wt-% C (the chemical composition corresponds with the mineral hydrohematite $2Fe_2O_3.H_2O$);

- The gray star-shaped oxides consisting of 66.2 wt-% Fe and 31.8 wt-% O (the chemical composition corresponds to the mineral hydrohematite $Fe_2O_3.nH_2O$);
- The gray–blue oxides consisting of 71.0 wt-% Fe, 26.5 wt-% O, and 0.3 wt-% C (the chemical composition corresponding to magnetite Fe_3O_4). It is necessary to stress that in the structure of the ring (Fig. 40) no metallic iron was found and that in all types of iron oxides approximately less than 0.3 wt. % of carbon was determined.

The results of the line point analysis (Fig. 40: b– line GH) are demonstrated in Fig. 42. The content of iron increases from the external to the internal surface of the ring. Near to the external surface the iron oxide composition corresponds to hydrohematite and near to the internal surface the iron oxide composition approximately corresponds to magnetite. Fig. 42 also demonstrates that in the middle of the ring wall thickness there is a thin layer consisting of copper oxides. The metallic copper and also tin–copper (bronze) are sporadically found in this layer. The chemical composition of those metallic components was determined by a microprobe analyser (location: Fig. 40: b – D, E and F).

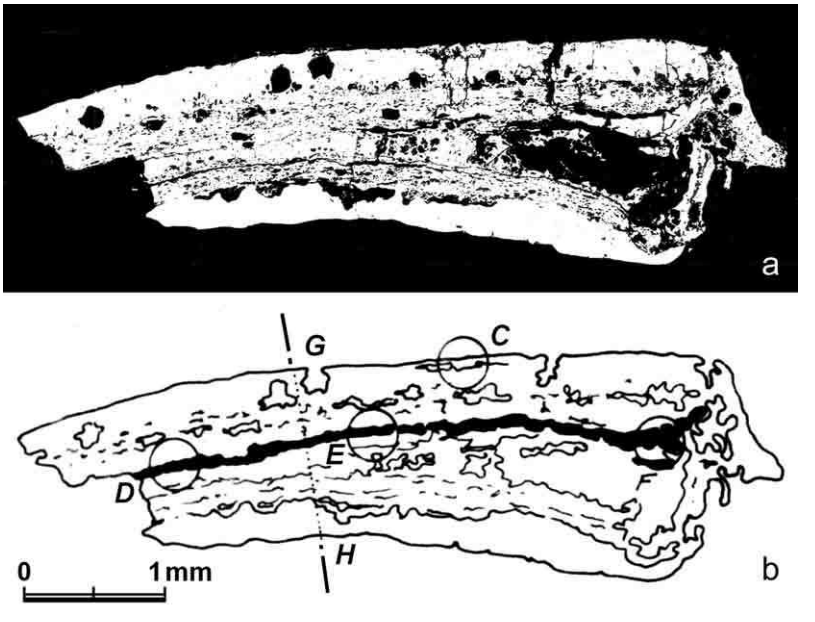

Figure 40: The cross-section of the prehistoric ring: a) the metallographic structure; b) the analytical scheme (K. Stránský).

Table 1: The results of the x–ray electron microprobe analysis of the prehistoric ring (location: Fig. 4b – C and Figs. 5, 6 [wt. %]).

Component	Fe	O	C	Σ	Colour*	Location
Goethite	62.5	36.0	0.32	98.82	light gray	a
Hydrohematite	65.3	32.8	0.28	98.38	gray	b
Hydrohematite	66.2	31.8	-	98.00	gray, star-shaped	c
Magnetite	71.0	26.5	0.30	97.80	gray-blue	d

* in light microscope

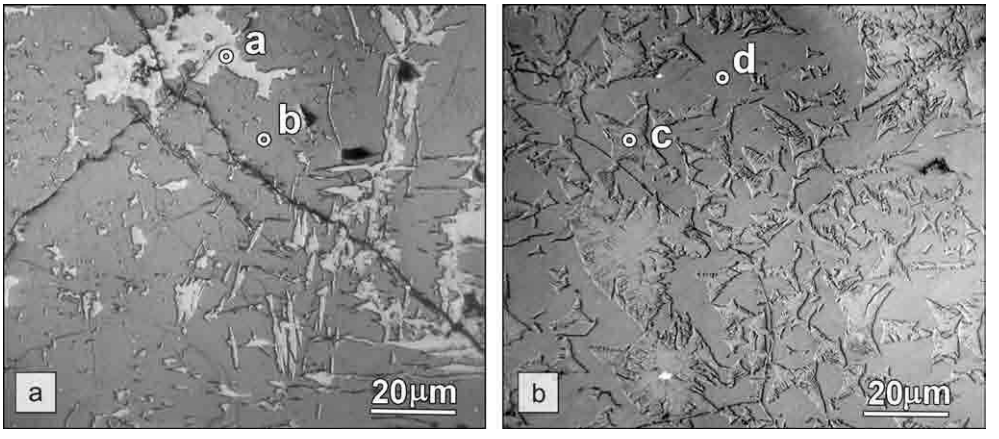

Figure 41: The microstructure of the iron ring: *left* (very near its surface) a – goethite and b – hydro-hematite; *right* (farther from the surface) c – hydrohematite in the shape of the star, and d – magnetite. Photograph by K. Stránský.

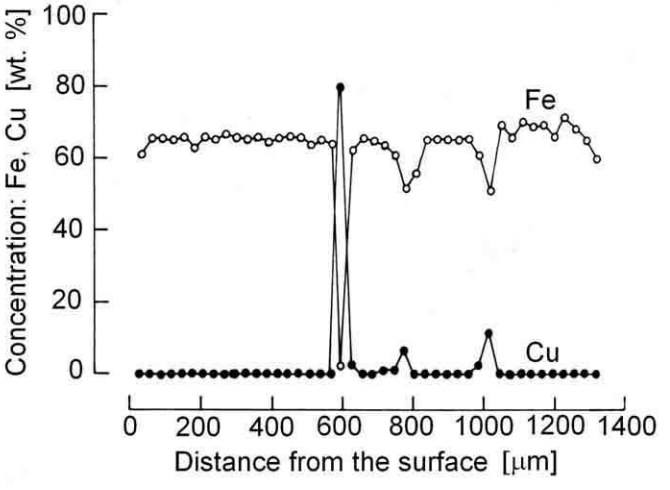

Figure 42: Line-point analyses of Fe and Cu – see Fig. 41: b – line GH. (K. Stránský).

Discussion and conclusions

The morphology of the ring microstructure (Fig. 40) is analogous to that of thin iron sheets, and of iron sheets that had been corroding for a very long time. It is therefore very probable that the prehistoric ring was made of an iron sheet and as such it represents a product of smithing.

It is also remarkable that the internal layer (Fig. 42) consists of copper oxides, metallic copper, and bronze. It may be assumed that the origin of the copper and tin in the iron ring is the composition of the primary iron ores.

The increasing content of iron and the decreasing content of oxygen (the complement to 100 wt-%) on Fig. 42 indicate that mineralization of the metallic iron ring passed from the external to the internal surface of the ring wall.

Professors Jareš and Absolon also published data about the density of the ring. The measured density of the entire iron ring was 6.98 (Absolon 1970, 215; Jareš & Absolon 1919). The density of the analysed ring fragment (Fig. 39: right /Plate XIV/) according to our measurements no more than 5.2. This value indicates the average density of iron oxides and so the fragment consists mostly of iron oxides. If the density of metallic iron is considered to be approximately 7.8 it could mean that there must be a certain amount of metallic iron in the prehistoric ring.

The prehistoric iron ring (including the fragment used to the analyses described) is probably in the private ownership of the Absolon family, which now lives abroad. For this reason it is unlikely that a complete analysis of the mysterious iron ring from the Bull's Rock cave will ever be made.

References

Absolon, K. 1946, 'Cast-Iron Ring 2500 Years Old: Further Discoveries in The Býčí skála Cave', *The Illustrated London News* Nov. 23, 946.

Absolon, K. 1970, *Moravský kras* 2 (Praha).

Jareš, V. & Absolon, K. 1919, 'Prehistorický železný prsten z Býčí skály na Moravě', *Časopis Moravského muzea zemského* (Brno).

Píšek, F. 1947, 'Je prehistorický prsten z Býčí skály z litiny?', *Hutnické listy* 2 (1), 9–10.

Stránský, K. et al. 1973: Stránský, K., Rek, A., Münsterová, E. & Ptáček, L. 1973, 'Z čeho byl vyroben prehistorický prsten z Býčí skály na Moravě', *Slévárenství* 21 (9), 360-366.

The craft of the Dacian blacksmiths

Ľ. Mihok and V. G. Kotigoroshko

The paper presents the results of chemical and microscopic analysis of slag and metallographic analysis of four iron swords found in excavations of the Dacian hillfort Malaya Kopanya, dated to 60 BCE to 100 AD. The finds resulted from the long-term excavation campaign of the Uzhgorod National University (which is still in progress). The analysis of many pieces of slag showed they originated in two sources: in the process of iron smelting in low shaft reduction furnace and in the process of the smithing of iron objects. Metallographic analysis of four iron swords showed four different production techniques, from a standard one to an excellent one. The reason for the swords found in a single complex around the Malaya Kopanya hillfort being produced by different methods needs analyses of more swords and other iron objects from the site.

Dacian settlement - Iron smelting - Smithy working - Slag - Iron swords - Metallography

Introduction

The swift changes in the political situation in the Carpathians–Danube region in the first half of the 1st century BCE is connected with the arrival of a young branch of the Goths and Dacians on the historical map of Europe, led by 'the first and the greatest king of the Thracians' – Burevista (*Inscriptiones* ..., 1916, I, 246).

The expansion of the Dacians resulted in the destruction of the La Tène culture of the area. In the Central Danube area the settlements and *oppida* of the Bojs and Tarrisks, in the Lower Danube area the settlements of the Skordisks, and in the West Pontis, from Olvium to Appolonium, the Greek cities were destroyed (Strabo, V, 1, 6; Crişan 1992, 27–35; Kotigoroshko 1999, 106). New data show that the Dacians came to the Upper Tisza North Thracian environment around 60 BCE. Here the *oppidum* of Halish–Lovachka was destroyed and a series of hillforts were built – Zemplín, Malaya Kopanya, Solotvyno, Bila Cerkva, and Ontcheshty (Kotigoroshko 2004, 398–99, Fig. 1).

Among these key centres of Dacian culture the Malaya Kopanya hillfort is considered to be one of the most important in terms of its size, its

protection systems, and the size of the studied area. It is important to note that the Malaya Kopanya is a very complicated series of settlements situated on the rim of the Chust–Rokosovo volcanic ridge which stretches over four hills. In the central position is the Gorodishche site, where the cultural layers are up to 4m deep. The Serednij Grunok and Chellenica sites were cemeteries.

In the Gorodishche hillfort site, where excavations have been taking place since 1977, tens of houses and economic and production artefacts have been excavated. Most of the artefacts relate to iron working (Kotigoroshko 1989, 36, 38). Thirty years of research at Malaya Kopanya resulted in the collection of huge amount of finds, many of them the products of blacksmiths. On the basis of a functional analysis iron products were classified into a small number of groups. The first of these consisted of blacksmiths' tools (anvil, tongs, chisels, drifts, etc).

The collection contained many tools for working wood, among which the most important were axes, chippers, carving chisels, wedges, and cramps. Agricultural tools and materials were also frequently found: ploughshares, scythes, sickles, and shears. Some artefacts were used for stone working, such as hammers. Objects associated with everyday life were represented by knives, buckle handles, nails, hooks, etc. Another group was formed by the implements used by fur workers, such as knives for skin cleaning, cutting edges, and needles.

Weapons made up a special group which included double-edged swords, spearheads, shot, eyes, remnants of shields, ring mail, etc. Especially important was the fighting knife which adopted the form of classical Dacian swords. Spurs and belts formed part of soldiers' equipment, whilst some decorations and parts of garments were also made from iron, including fibulae, buckles, and rings (Kotigoroshko, 2004, 405, Fig. 4–5).

An analysis of the blacksmiths' production techniques was carried out on two contemporary sites, Zemplín (Mihok *et al.* 1993) and Malaya Kopanya (Bidzilija *et al.* 1983, 100; Hollý *et al.* 1995, 398–401). The analyses were carried out in two different institutions, the Institute of Archaeology of NAN, Ukraine, and the Technical University in Košice, Slovakia. Analysis of iron objects from the Zemplín site (axe, knives, spearhead) documented standard blacksmiths production techniques comprising cementation and pack-forging of metal, but there was no evidence of quenching.

The blacksmiths working on the Malaya Kopanya settlement used more sophisticated production techniques. Metallographic analysis of iron objects (scythes, sickles, axes, knives, spearheads, chisels, and a bracelet) showed a mastery of both hot pressure welding and the treatment of final products. Iron objects for heavy-duty use were produced using sophisti-

cated techniques such as quenching, welding of carburized components, heat treatment, etc. Local cementation of tool edges or working parts, followed by quenching, is one of many examples.

The paper presents analysis of slag and metallographic analysis of four iron swords found in sites of the Malaya Kopanya complex.

Analysis of slag finds

In the course of research on the Dacian hillfort of Malaya Kopanya, in addition to a rich collection of metallic objects with different functions and forms, a great deal of slag was collected in an area of 1.95ha. The slag was found both as fills and in cultural strata. Slag was collected over the entire area of the hillfort at depths varying from 0.3m to 1.9m, and in special cases even as deep as 2.2m. The large amount of objects in iron and non-ferrous metals are proof of intensive production of forged objects on the hillfort, and this relates directly to the production and processing of iron in this area. The existence of a blacksmiths' workshop was recorded in the north-east section of this area. The workshop was 8m × 3.4m in area and was built in wood, stone, and clay. The hearth was situated in the middle of the shop and was covered by stone (Mihok *et al.* 1995).

The slag finds from this area were classified into three groups. The first group, A, consisted of three pieces of slag: samples A1, A2, and A3 were roughly bowl-shaped and their surfaces had many fused areas. Their weights ranged from 458.9g to 625.5g. They were dark grey in colour with some brown and rusty several surfaces; on sample A1 a few charcoal prints were observed together with a few fine pores; sample A2 was very porous when fractured; sample A3 had visible charcoal prints and was very porous on the surface.

The second group consisted of two similar samples; one of them, B1, was light brown and rusty in colour and very porous on its surface, and it had the shape of a larger bowl (Fig. 43).

The third group, C, consisted of seven samples of slag. Samples C1, C3, and C6 were bowl-shaped at the bottom; they were dark grey-brown and rusty coloured and very porous. The samples were relatively heavy: C1 584.3g and C3 790.2g. Sample C3 had visible charcoal prints on the surface. Sample C6 weighed 435.5g.

Samples C2, C4, and C7 were irregular in shape and very porous. They were grey-brown in colour with rusty places on the surface. Sample C2 was relatively light (359.3g) with imprints on the surface. This group also contained sample C5, which had the shape of larger bowl with a smooth base and was broken in two parts. The sample weight was 1026g and it

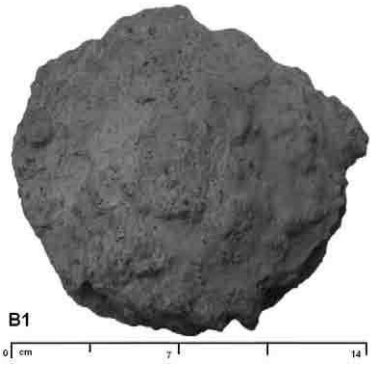

Figure 43: The larger bowl of sample B1. Photograph by Ľ. Mihok.

Table 2: Chemical analysis of slag samples, wt.-%.

Samples	SiO_2	$Fe_{tot.}$	CaO	MgO	Al_2O_3	MnO	FeO	P
A1	23.52	51.94	5.04	3.20	2.85	0.94	51.73	0.057
A2	29.70	43.56	2.80	3.60	2.85	0.18	31.90	0.048
A3	26.42	43.56	3.36	4.00	2.65	0.16	46.70	0.055
B1	32.94	29.60	2.80	4.80	2.44	0.13	7.61	0.045
C1	55.96	27.92	3.36	3.20	2.44	0.16	17.24	0.064
C2	38.62	40.77	3.92	3.20	2.65	0.12	48.13	0.067
C3	28.52	39.09	2.80	1.20	2.65	0.06	34.48	0.058
C4	83.44	7.81	4.48	2.00	2.04	0.09	5.02	0.050
C5	27.68	35.74	2.80	4.00	2.24	2.58	43.39	0.048
C6	24.06	54.73	2.80	3.20	2.04	0.06	55.75	0.050
C7	27.80	37.97	3.92	3.20	2.04	0.07	33.33	0.052

was dark-grey in colour and porous when fractured.

Chemical analysis of samples

Chemical and microscopic analyses were performed on the samples. For this purpose they were cut in two parts by diamond saw, the first one being used, after grinding, for classic chemical analysis. The results of the chemical analysis of eleven slag fragments are shown in Table 2.

It can be seen from Table 2 that sample C4 is not slag: it is inorganic material with high silica and low $Fe_{tot.}$ contents.

The next four samples, A1, A2, A3, and C6, were slag from low shaft furnaces for iron smelting. Silica contents varied from 24.06% to 29.70%

and $Fe_{tot.}$ contents from 43.56% to 54.73%. The total iron contents in the samples nearly corresponds with the FeO contents (i.e. most of the iron in the samples is in the form of FeO). The low contents of CaO, MgO, and Al_2O_3 show that no additions of slag-formers (fluxes) were made.

The chemical analysis shows that samples B1, C1, C2, C3, C5, and C7 are forging slags resulting from smithy production. The samples had lower $Fe_{tot.}$ contents (27.92–40.77%) and higher silica contents (27.68–55.96%) than slags from shaft furnaces.

Microscopic analysis of samples

Metallographic surfaces were prepared by grinding and polishing of the other parts of the samples assigned for microscopic analysis. Structural components were observed using metallographic optic microscopes.

Microscopic analysis of samples A1, A2, A3, and C6 showed them to be slag from shaft furnaces. A silicate matrix and wüstite Fe_xO was found in the structure of the samples. Sample A1 revealed many dendrites of wüstite. The structures of the samples were formed of a silicate matrix with dendrites of wüstite (Fig. 44).

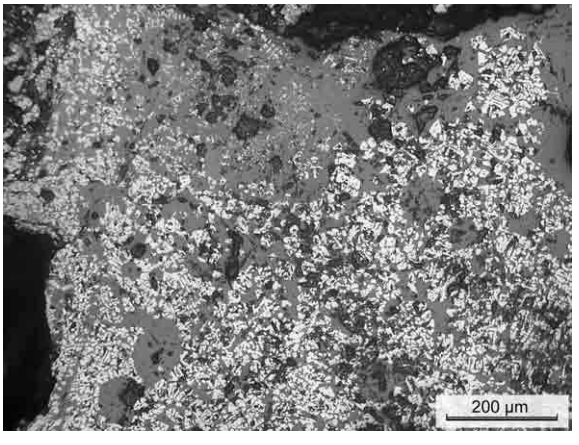

Figure 44: Sample C6 with many wüstite dendrites. Photograph by Ľ. Mihok.

Microscopic analysis of samples B1, C1, C2, C3, C5, and C7 showed them to be forging (smithy) slag, characterized by a mostly silicate structure made up of components of fayalite $2FeO.SiO_2$ and ferrous olivines basis. Only a low content of wüstite Fe_xO was found in the structures, in form of fine dendrites and blocks of wüstite globules. Small pieces of corroded metallic iron and remnants of silica sand were found in the structures, whilst in some samples remnants of charcoal were observed.

In the structure of sample B1 a silicate matrix with fine dendrites of

wüstite, remnants of charcoal, corrosion, and silica sand was detected (Fig. 45). A silicate structure made up of components of fayalite $2FeO.SiO_2$ which originated from the reaction of scale and silica sand, as well as a great deal of corrosion products (Fig. 46), were detected in sample C1. Very small dendrites of wüstite, corrosion products, and metallic iron in the silicate structure were found in the structure of sample C3.

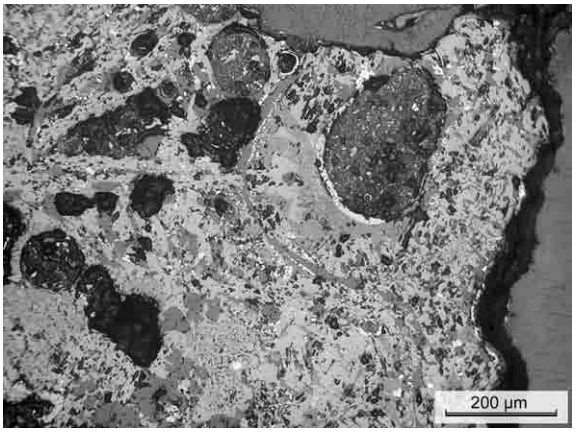

Figure 45: Remnants of silica sand in sample B1. Photograph by Ľ. Mihok.

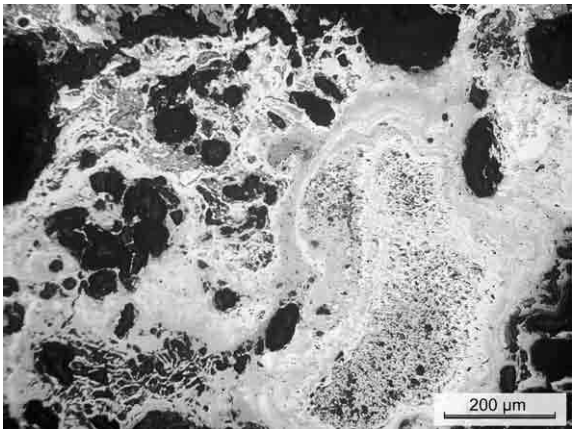

Figure 46: Corrosion products, sample C1. Photograph by Ľ. Mihok.

Metallographic analysis of four iron swords

The Uzhgorod National University expedition in 2002–2003 excavated seven graves in the Serednij Grunok site in which iron covers of shields (graves 2, 3–4), bent double-edged swords (graves 2, 6) and spearheads

(grave 2) were found. A central fragment of another sword was found on the periphery of the site. Study of the weapons and associated ceramics made it possible to date the burials to the end of the 1st and beginning of the 2nd centuries AD.

In 2007 a new excavation began in the Chellenica site, 200m northwest of the central part of the settlement. This where seven earthen walls protected the Malaya Kopanya settlement on the side of the 'Chust Gate,' through which foreign tribes entered the southern part of the Upper Tisza region and the Carpathian basin as a whole. In the course of the site research six burials were discovered containing rich material. A special group included a sword that had been bent three times along with the heads of rods and darts. The stratigraphy of the site showed that the graves dated to the first half of the 1st century BCE.

Four swords were selected for metallographic analysis, three from the Serednij Grunok site and one from the Chellenica site. Photographs of the studied objects are shown in Fig. 47–50, along with the results of metallographic analysis. All four of the objects contained enough solid metal for sampling, by means of cross-section cuts that made it possible to study the distribution of metallic iron structures.

The samples were mounted in resin and the surfaces for metallographic analysis were prepared in the normal way by grinding using metallographic papers and polished with diamond pastes. High-quality metallographic surfaces were observed under metallographic optical microscope, first in the non- etched state so as to identify non-metallic inclusions and any discontinuities in the iron. The surfaces were then etched with nital (2% solution of nitric acid in ethyl alcohol) and the structures revealed by etching were studied again by optical microscope. All the significant microscopic features were recorded photographically.

The results of the metallographic analysis are presented in Fig. 47–50. Each figure consists of a photograph of the object, a sketch showing where samples had been taken, and a drawing of the metallographic surface. Structures observed at points marked on the drawings of the metallographic surfaces are also shown.

Sword 1 – Serednij Grunok

Sword 1 was found in a cultural layer during the 2003 excavations. The metallographic analysis of the sword is shown in Fig. 47, which also indicates where the sample was taken.

Inclusions of smelting slag, smithing inclusions, and unreacted scales were observed on the surface before etching. A smelting slag inclusion

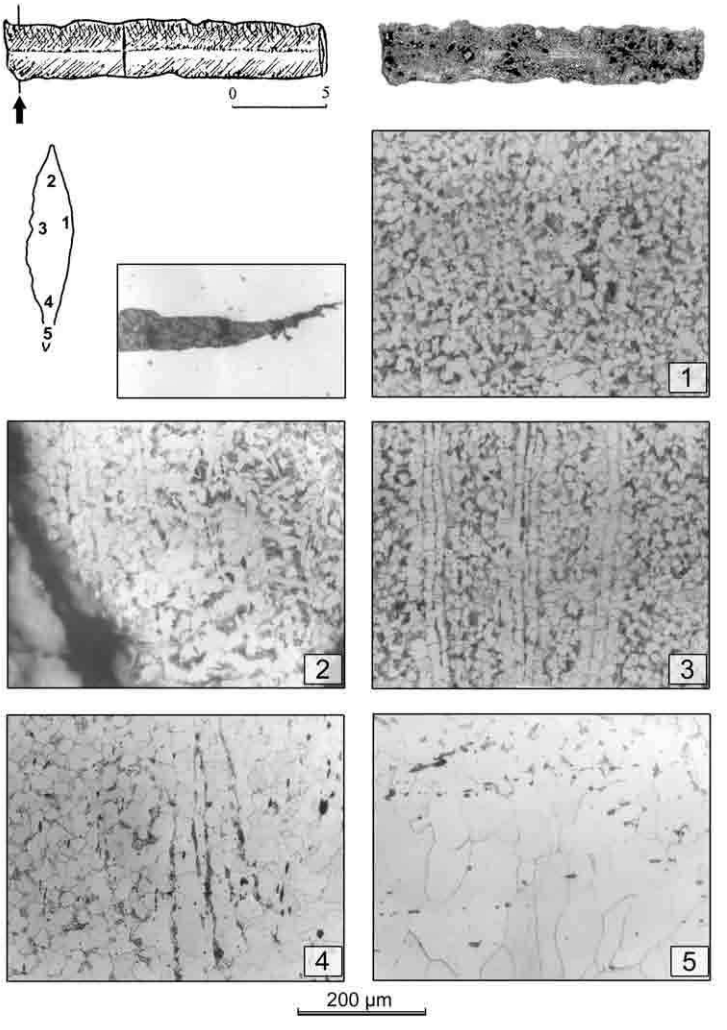

Figure 47: Metallographic analysis of sword 1. Microphotographs by Ľ. Mihok.

can be seen at the bottom right of the photomicrograph. After nital etching a ferritic–pearlitic structure with about 0.25% C was observed over nearly the entire surface (photograph 1). No increase of carbon on the edge can be seen in photograph 2. There is a typical banded structure (photograph 3), also observed elsewhere, caused by increased phosphorus in the metal; this is also revealed by the presence of phosphidic eutectics. At some points on the surface (photograph 4) only the ferritic structure of non-carburized iron was found. A coarse-grained ferritic structure (photograph 5 was found on the other edge of the sword. Here the pearlitic content in the structure (i.e. the carbon content in the iron) was characteristically decreased.

This mildly carburized iron is suitable for making swords, but there was no evidence of special techniques for hardening the edges. The low or non-existent contents of carbon on the other edge may be the result of secondary decarburization, though it is possible that the sword was single–edged.

Sword 2 – Serednij Grunok

The metallographic analysis of sword 2 is shown in Fig. 48. Particles of smithy slag and partly reacted scales, deformed to thin bands, were observed on the metallographic surface of the sample in the unetched state. The lower part of the surface showed no inclusions.

Nital etching revealed an interesting distribution of structures. A band of carburized pearlitic iron (photograph 2) stretched from the upper edge that was in contact with a very mildly carburized iron (about 0.1% C) with a ferritic pearlitic structure (see photograph 1); both are shown at the point of contact between them in photograph 3. This double layered structure covered about two-thirds of the metallographic surface. A carburized ferritic–pearlitic structure with about 0.3–0.4% C extended down to the other edge, as shown in photographs 4 and 5. No inclusions were found in this part of the surface.

The part of the sword that was analysed showed it to be made up of three different iron semi-products in the form of plates joined by smithy welding. Both edges of the sword were hardened by carburization. The upper edge was formed of pearlitic carburized iron and the lower of carburized ferritic–pearlitic iron. The technique used for producing this sword was different from that used for sword 1. It was satisfactory in quality, and it was double–edged.

Sword 3 – Serednij Grunok.

The results of the metallographic analysis of sword 3 are shown in Fig. 49 /Plate XV/. Once again the sample was taken by cutting a cross-section. Thin bands of smithing inclusions were observed on the unetched metallographic surface of the sample, but they were fewer than on sword 2.

After etching with nital a relatively homogeneous structure was observed over the whole surface. The structure was evidence of carburization of the iron to about 0.6% C. After finishing the sword in its final shape was heated to heat-treatment temperature, quenched, and tempered. The

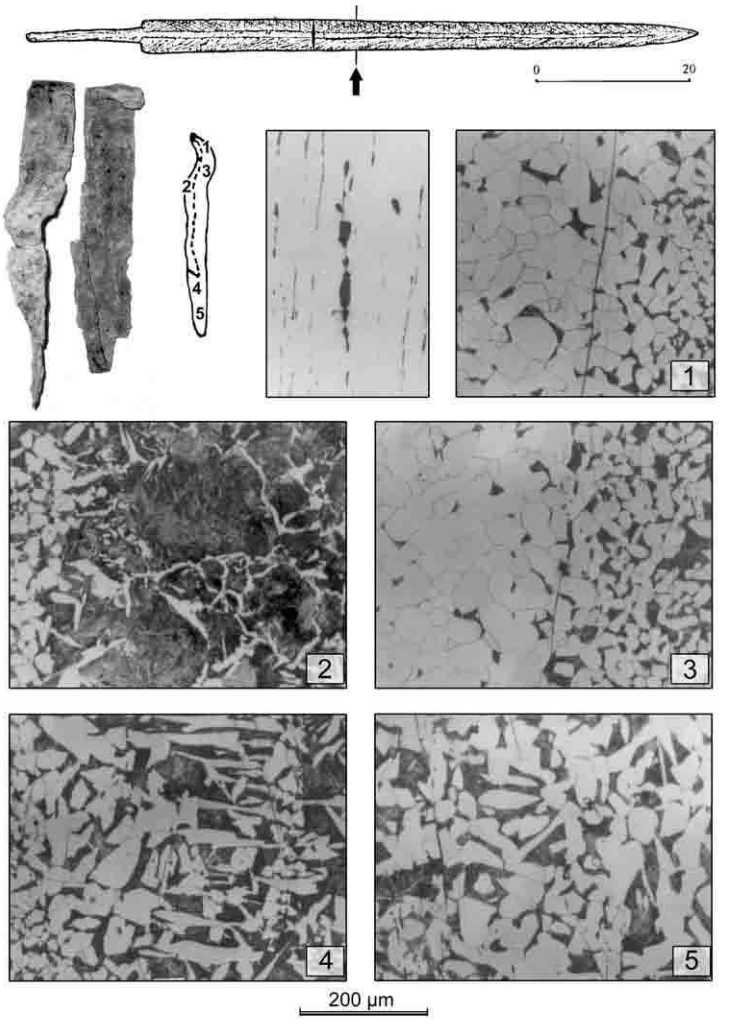

Figure 48: Metallographic analysis of sword 2. Microphotographs by Ľ. Mihok.

structures are shown in photographs 1–4

Sword 4 – Chellenica

The metallographic analysis of sword 4 is shown in Fig. 50 /Plate XVI/. The sample was, once again, taken by a cross–section cut. Long thin bands of forging inclusions were observed on the metallographic surface before etching. Etching revealed the following distribution of structures. On one end of the metallographic surface was found a ferritic–pearlitic structure of mildly carburized iron (photograph 1). Lower down from the upper

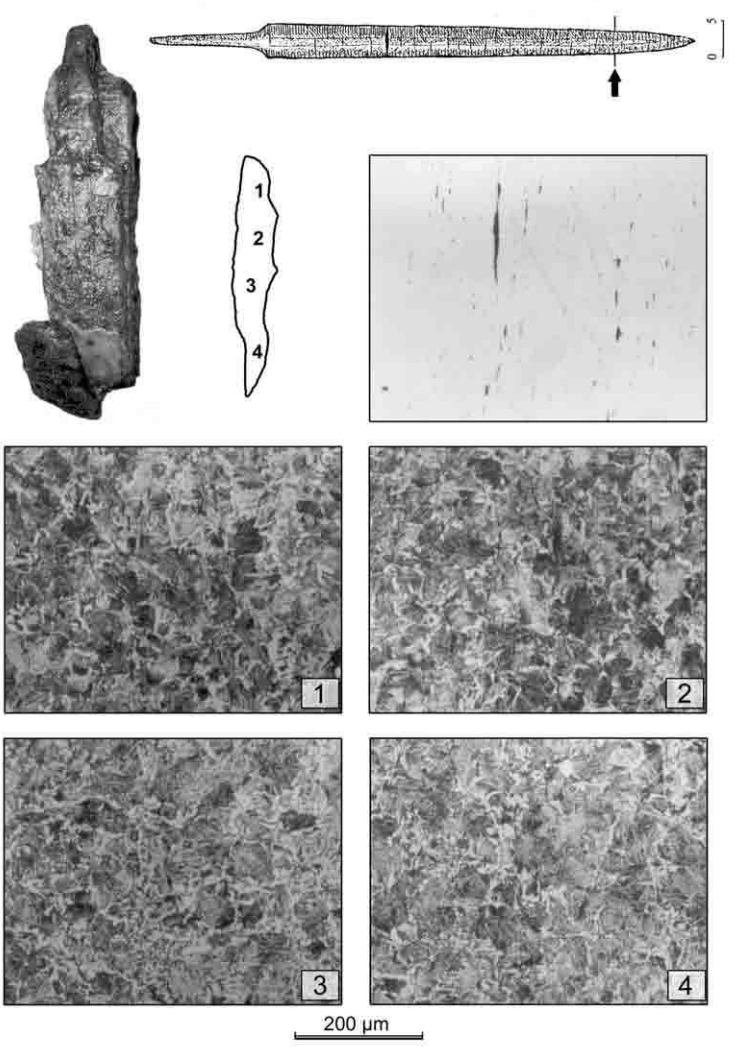

Figure 49: Metallographic analysis of sword 3. Microphotographs by Ľ. Mihok.

end on one side of the metallographic surface ferritic–pearlitic structures of carburized iron were found. The carbon content decreased towards the other side, where only ferritic structures of non-carburized iron were found (photographs 2, 3, and 4). Near the other end of the metallographic surface carburization of iron on one side was more intensive (photograph 5), whilst at the extreme edge of the metallographic surface all that was to be found was a pearlitic structure of heavily carburized iron (photograph 6). The edge of the sword was most probably formed in this place. The sword was made from non-carburized iron semi-products. After shaping was completed the sword was carburized on one side, but more intensively

on the edge. The analysis shows that the sword was single-edged and of good quality.

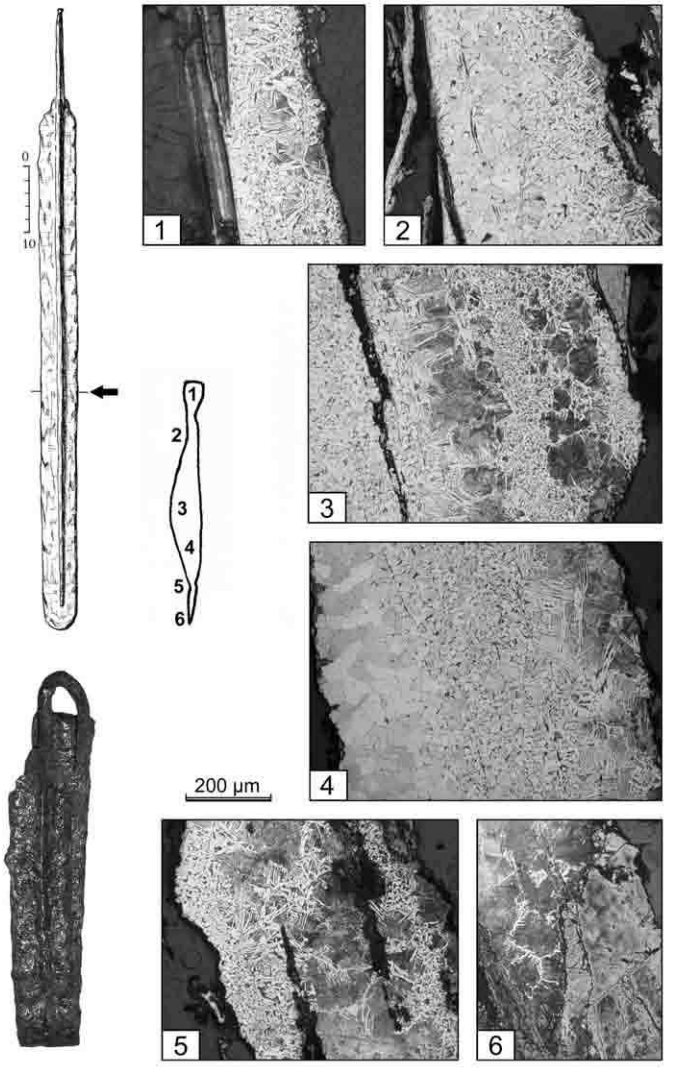

Figure 50: Metallographic analysis of sword 4. Microphotographs by Ľ. Mihok.

Discussion

Two types of slag were found on the archaeological site of Malaya Kopanya. One of them was smelting slag, resulting from iron-ore reduction in a small bloomery furnace. The slag was characterized by a silicate matrix, in which mostly dendrites of wüstite Fe_xO crystallized. The second

group consisted of smithy (forging) slag, resulting from the preparation of iron materials and artefacts by working in a smithy. Typical smithy slag has a ferrous silicate matrix, containing corrosion products, traces of silica sand, and fragments of charcoal. The results thus confirmed that both blacksmiths' activities and iron smelting took place at the site.

Metallographic analysis of the four swords from Malaya Kopanya has made it possible to describe and compare the smithing techniques used for the production of the swords. The results of the research can, moreover, be compared with similar ones resulting from the analysis of groups of contemporary iron objects found on the territory of Slovakia.

Two swords were found in graves 78 and 108 of the Zemplín cemetery, dated to the same period (Mihok *et al.* 1993; Budinský-Krička & Lamiová-Schmiedlová 1990), which were not analysed metallographically. The only sword suitable for comparison purposes is a Roman sword from Varín (Mihok & Pieta 2004). The other groups of Roman and La Tène iron objects did not contain swords, only other types of iron weapons and mostly economic objects.

All four of the analysed swords from the Malaya Kopanya sites were produced by different blacksmithing techniques. One of the swords from the Serednij Grunok site was made from an iron semi–product carburized up to 0.25% C. No additional carburization of the edge(s) was made. The sword was single–edged and its quality was not exceptional. The second sword was made by smithy welding of three iron semiproducts with different properties. Both edges of the sword were made from carburized iron. The sword was double–edged and its quality was exceptional. The third sword was prepared in a very different way. It was made of highly carburized homogeneous iron. After being given its final shape the sword was reheated, quenched, and tempered. The production technique was sophisticate and the quality of this double-edged sword was very high.

The sword from the Chellenica site was made from uncarburized iron semiproducts; the sword was then carburized on one side of the blade, with the most intensive carburization on the edge. The reason for carburizing only one side of the blade is not clear. This single-edged sword was of good quality.

The 2nd century AD sword from Varín (north–west Slovakia) was made by forge-welding a few iron semi-products. The most heavily carburized semi-products were put on both sides of the sword, where the cutting edges were made, so as to produce a double-edged sword. The handle and the part adjoining to the handle were made of low-carbon iron. After the sword had attained its final shape it was reheated and the lower part of the blade was quenched and tempered. The quality of the sword, dated to the Púchov culture, was very high.

The author had at his disposal the analyses of five iron swords, all dated to the same period. The results of metallographic analysis were different, however, demonstrating different techniques for making iron swords. This was understandable when comparing the Roman sword from Varín with those from the Malaya Kopanya sites. But why were there such marked differences among the Malaya Kopanya swords? Were these due to the status of the person who ordered the sword, to changes in production techniques, or simply to the purposes for which the swords were made? Might they have been made at other production centres and not in Malaya Kopanya itself? It is probable that more research will be able to answer these questions.

The sophisticated production methods of the Malaya Kopanya blacksmiths were also documented by the analysis of sixteen iron objects (Pribulová et al. 2000). A special feature of the Dacian blacksmiths' technique was the very frequent use of carburization. When artefacts intended for demanding uses were first made they used mildly carburized iron semi-products. After shaping the object by welding and hammering the blacksmiths heavily carburised working parts such as edges or points. Implements such as a scythe, sickle, hammer, axe, and lances analysed in this study were made using this technique. However, the Dacian blacksmiths only used this technique in cases when it was necessary. To produce less demanding parts of the artefacts – the handles of chisels, for example – they used uncarburized semi-products or even scrap iron from the smithy. Facts such as these are evidence that blacksmiths had a deep knowledge of the material properties of iron and thus were able to made appropriate selections according to intended use.

Metallographic analysis has revealed that different techniques were in use for making knives. The smaller ones were probably made from a single semi-product; the whole knife then being heavily carburized. For making larger ones the so-called 'sandwich' technique was used, whereby three mildly carburized semi-products in the form of thin platelets were forge-welded together. The edge of the knife was then heavily carburized and quenched.

The Dacian blacksmiths also paid special attention to manufacturing some 'consumable' products such as wedges or nails. The wedge was produced by welding together three semi-products. Once the final form was obtained the wedge was surface-hardened by carburization. Nails were produced from mildly carburised iron material. The resulting structural homogeneity and very low content of non-metallic inclusions were remarkable.

Conclusions

This paper presents the results of the analysis of slag and four iron swords found in the archaeological excavation of the Malaya Kopanya sites. The results are as follows:

- Four pieces of slag were identified as slag from low shaft furnaces for iron smelting. They were typical by virtue of their lower silica contents and higher $Fe_{tot.}$ contents. Low CaO contents showed that no slag formers were added during the processes.
- Six pieces of slag were identified as resulting from smithy working. The origin of the slag and its composition reflect specific forging processes.
- The samples had all the attributes of smithing slag – chemical analysis, corrosion products in the structure, ferrous silicate matrix, blocks of wüstite globules or fine dendrites of wüstite in structures, and traces of charcoal and silica sand. This material collected in the forging hearth in the course of the manufacture of iron objects.
- Each of the swords that was analysed was produced by a different smithing technique. Sword 1 from SerednijGrunok was made from mildly carburized iron and no second carburization of the edge was found. Sword 2 from Serednij Grunok was made by welding together a few iron semi-products, following which both edges were heavily carburized. Sword 3 from Serednij Grunok was made from carburized iron, and then quenched and tempered.
- Sword 4 from Chellenica was only carburized on one side of the blade and most intensively on the edge.
- It was not clear why the swords found in one complex around the Malaya Kopanya settlement were produced by different methods. Only analysis of more swords found at Malaya Kopanya is likely to help solve the problem. Analysis of a Púchov Culture sword from Varín (Slovakia), used for comparison purposes, also revealed methods of production that were very different from the swords from the Malaya Kopanya sites.

References

Bidzilija,V.I. et al. 1983: Bidzilija,V.I., Voznesenskaya, G.A., Nedopako, D.P., & Pankov, S.V. 1983, *History of Smelting and Working of Iron on the Territory of USSR (3rd Century B.C. – 3rd Century A.D.)* (Kiev).

Budinský-Krička,V. & Lamiová-Schmiedlová, M. 1990, 'A Late 1st Century B.C. – 2nd Century A.D. Cemetery at Zemplin', *Slovak Archaeology* 2, 245-344.

Crişan, I.H. 1992, *Graniţa de Nord – Vest a Dacii Ephermeris Napocensis* II, 27-36.

Hollý, A. et al. 1995: Hollý, A., Mihok, Ľ. & Kotigoroshko, V.G. 1995, 'Metallographic Analysis of Dacian Iron Objects', in *Metallography'95* (Košice), 398-401.

Inscriptiones antiquae orae septentrionalis Ponti Euxini Graecae et Latiae. Petropoli, 1916, I, 246.

Kotigoroshko, V.G. 1989, 'Settlements on the Beginnings of the 1st Millennium A.D. in the Upper Tisza Region', *Soviet Archaeology* 37 (1), 21-67.

Kotigoroshko,V.G. 1999. 'Ethnopolitical Aspects of Upper Tisza Region Inhabitation in the 1st Millennium B.C. – 1st Millennium A.D.', in *Rumanian – Ukrainian Relations, History and Present* (Satu Mare), 101-118.

Kotigoroshko,V.G. 2004, 'Inhabitation of the Upper Tisza Region on the Beginnings of the 1st Millennium A.D. Thracians and Circumpontic World', in *Proceedings of the Ninth International Congress of Thracology, Chişinău 2004* (II), 396-417.

Mihok, Ľ. & Pieta, K. 2004, 'Metallographic Analysis of Iron Sword, Dated to Roman Period, Found in Varín', in *Z dějin hutnictví* 34 (Praha: Rozpravy Národního technnického muzea v Praze 188), 16-20.

Mihok, Ľ. et al. 1993: Mihok, Ľ., Miroššayová, E. & Veselovská, J. 1993, 'Metallographic Analysis of Iron Objects Dated to Late Laténe Age from Zemplin', *East Slovak Antiquity* IV, 95-108.

Mihok, Ľ. et al. 1995: Mihok, Ľ., Kotigoroshko,V.G., Hollý, A., Pribulová, A. & Cengel, P. 1995, 'Smithy Production in Dacian Hillfort Malaya Kopanya', *Study News of the Archaeological Institute of SAS* 31, 65-88.

Pribulová, A. et al. 2000: Pribulová, A., Mihok, Ľ. & Kotigoroshko, V.G. 2000, 'Production Methods of Dacian Blacksmiths. Metallgewinnung und – Verarbeitung in der Antike (Schwerpunkt Eisen)', *Archaeologica Slovaca Monographiae* Tomus III (Nitra), 163-176.

Strabo, *Geographica* Reprint 1994 (Leningrad).

Early medieval knife manufacture in Britain; a comparison between rural and urban settlements (AD 400–1000)

E. Blakelock and G. McDonnell

Iron knives are frequently found on early medieval sites and provide archaeometallurgists with good opportunities to investigate methods of manufacture, the alloys available, the skills of the blacksmith, and therefore the iron economy as a whole. Previous studies of knives have revealed some clear differences in knife manufacture in early medieval (400–1000) England, when comparing urban settlements with rural cemeteries. This paper compares knives found at rural and urban settlements. Two knife assemblages from rural sites, Wharram Percy and Burdale, have been analysed and compared with contemporary urban settlements at Hamwic and York. This study has shown that, while there is no difference in knife manufacture between these sites, there are other differences, the most dramatic of which is the smaller number of heat-treated knives found in the rural settlements.

Iron - Knives - Metallographic Analysis - Early medieval England - Urban - Rural

Introduction

Over the last 50 years numerous archaeometallurgical studies of iron artefacts have been carried out, by many different researchers, in countries across Europe. The knife is one of the most common iron artefacts recovered during excavations, and they are particularly common on many early medieval sites. Knives are often composite artefacts utilizing the different properties of each iron alloy available, and also different blacksmithing skills, e.g. heat-treatment, welding, etc. Therefore metallurgical analysis of knives can provide an insight into ironworking technology. The blacksmith was vital both to urban settlements, by creating tools for craft workers, but also to rural settlements by creating and repairing agricultural tools.

During a review of the metallographic analysis of English early medieval knives it became clear that there were patterns emerging, including a distinct difference between those from early medieval settlements and

cemeteries. One possible explanation is that there was a clear difference in knife technology and manufacture between urban centres and more rural communities. Therefore the primary aim of this paper is to investigate this theory, and to better understand ironworking technology in both urban and rural settlements. This paper presents the results from the analysis of 27 knives from two early medieval rural settlements: 13 knives from Wharram Percy and a further 14 knives from Burdale. This data will then be compared to knives from Fishergate and Coppergate, York and Southampton (Hamwic) both contemporary urban settlements.

Background

During the 7th and 8th centuries many centres of trade and industry were established in Britain (Hamerow 2002). These settlements, including Hamwic and York, were organized with streets and defined plots for properties and were home to small industries producing all sorts of goods, including iron tools such as knives (Andrews 1997, 1–18). During this period rural settlements in Britain also became more formalized with the introduction of planned layouts, fenced enclosures, and the construction of the first large 'great hall' buildings (Hamerow 2002, 94–99).

The ironworking industry during the early medieval period is thought to have consisted of local manufacture for local needs (Hamerow 1999). Very few early medieval smelting sites have been identified in England. The majority of those discovered so far were associated with high-status centres, such as Ramsbury and Flixborough (Hamerow 2002, 189) or rural settlements like Bestwall, Dorset (Slater & McDonnell 2002). There is scant evidence for urban smelting in the early medieval period (Ottaway 1992, 477–78). On the other hand most early medieval settlements have produced some evidence for smithing. This is to be expected, especially since smiths would have been required to manufacture and repair the iron artefacts used. It is likely that there were different types of smithy, from permanent 'full-time' workshops to forges where occasional smithing operations were carried out. Even so, the evidence from this period is sparse; while smithing slag has been recovered, very few smithy structures have been identified (McDonnell 1989; Stamper & Croft 2000, 155–66; McDonnell *et al.* forthcoming). Smithing slag has been identified at all the settlement sites discussed in this paper.

The smith required a stock of iron from which to produce artefacts. Four basic types of iron were available; ferritic iron, which contains few alloying elements (less than 0.1%), phosphoric iron containing between 0.2 and 1% phosphorus, and steel which contains carbon as the main alloying

element (McDonnell 1989). The final type of iron, often present on early medieval sites, is piled iron which refers to metallographic structures in which alternating bands of different irons are present (McDonnell 1989).

Many knives are composite artefacts with small amounts of steel added to the knife during construction to create a cutting edge. In 1986 Tylecote and Gilmour produced a typology of six different methods of manufacturing knives which were further divided into subgroups (Tylecote & Gilmour 1986, 2–7), this typology has since been simplified by McDonnell (Blakelock & McDonnell 2007), Fig. 51.

During the last 50 years the metallurgical examination of early iron implements has been undertaken in numerous countries, especially in north-east Europe (Piaskowski 1987). In 1959 Kolchin published the results from one of the largest and most comprehensive analysis projects of iron knives from medieval Novgorod (Thompson *et al.* 1967). Other smaller-scale but equally important studies of early medieval iron artefacts have been carried out in England, York and Hamwic (McDonnell 1987b; McDonnell 1987a; McDonnell 1992), Ireland (Scott 1991, 99–150), Poland (Piaskowski 1961), Bohemia (Hošek 2003), and at sites such as Helgö, Sweden (Tomtlund 1973).

In 2005 a new review of the metallurgical analysis of knives from early medieval England was carried out (Blakelock & McDonnell 2007). This revealed some distinct patterns in knife manufacture, with clear differences between those from settlements and cemeteries. Early medieval cemeteries had a wider variation in knife-manufacturing technology while those from settlements were dominated by knives manufactured by butt-welding a steel cutting edge to an iron back (type 2). This led to several theories, one of which is that these patterns are due to differences in manufacture in urban centres compared with that in rural settlements. Another possibility is that the difference reflects changes over time, or alternatively that some knives were being manufactured specifically for burial (Blakelock & McDonnell 2007, 51–52). The survey also suggested possible geographical variation in the alloys used, e.g. the majority of knives with phosphoric iron were recovered from excavations in York (Blakelock & McDonnell 2007, 55).

The review demonstrated that there was a lack of data for rural settlement sites. To address this issue knives from two rural settlements in East Yorkshire were selected for analysis. Wharram Percy and Burdale are typical rural settlements located on the Yorkshire Wolds. Wharram Percy has clear evidence for occupation from prehistoric times onwards and there is substantial evidence for an early medieval settlement with an associated smithy dated to the 7th–8th century (Stamper & Croft 2000, 155–66). At Burdale there is evidence for a multi-phased Anglian farmstead dating to

the 8th–9th century (Richards, in preparation).

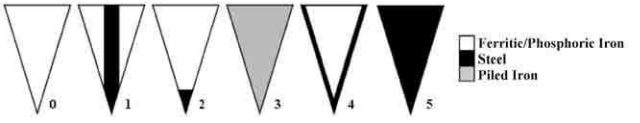

Figure 51: Knife manufacturing typology based on blade cross-sections (adapted from Tylecote & Gilmour 1986). 0 = all ferrite (or phosphoric iron) with no steel cutting edge, 1 = steel core flanked by ferritic or phosphoric iron, 2 = steel cutting edge butt-welded to the iron back, 3 = piled or banded structure throughout the section, 4 = steel forms a jacket around an iron core, 5 = all steel blade.

Methodology

Prior to sampling the knives were recorded using descriptions, sketches, photographs, and x-radiographs. The shape of the knife back and tang interface were recorded, as was the amount of wear present on the cutting edge (Fig. 52). The knives were sampled by removing a section or two half- sections of metal using a Microslice diamond wafering blade. The sections were then mounted in Buehler VariDur 200 cold-setting resin, ground and then polished to a one micron diamond finish. The samples were examined using a Nikon Optiphot reflected light microscope and the microstructures present in the knives were noted, both prior to and after etching in 4% nital. The grain sizes were recorded using an ASTM grain size standard at ×100 magnification. A Vickers hardness test was also carried out on these sections, using a load of 200g for 15 seconds. The chemical composition of the metal was determined using scanning electron microscopy with energy dispersive x-ray analysis (SEM-EDS). Spectra were collected from several areas in each knife, at 20kV and 2nA for 100 seconds live time, and calibrated with a cobalt standard.

Results

Wharram Percy

Forty-four knives were recovered during excavations at the South Manor at Wharram Percy. Seventeen knives were dated to the early medieval period, of which eleven came from deposits dated to the 7th–8th century, contemporary with the Saxon smithy. Thirteen knives were chosen for metallographic analysis, from contexts ranging from the 7th to the 10th century (Table 3, Fig. 54 /Plate XVII/). The cutting edges of six of the

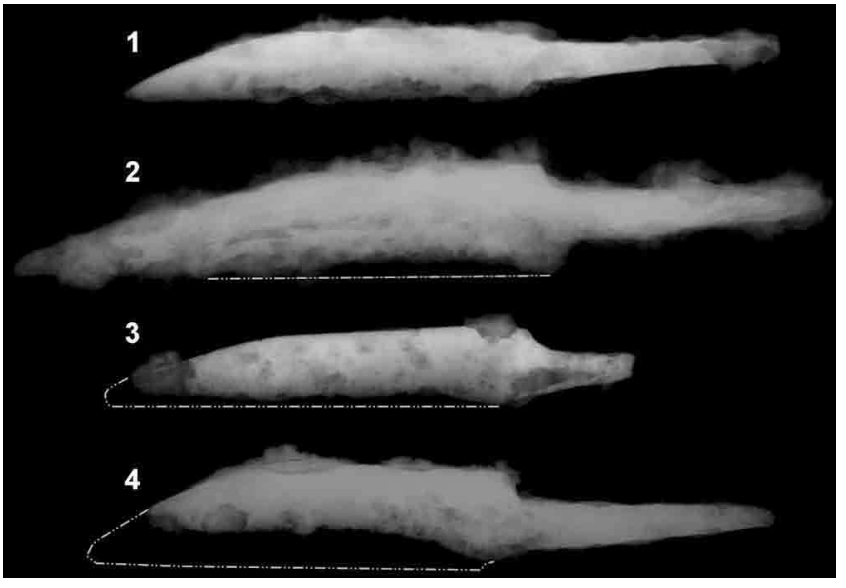

Figure 52: X-radiographs of knives from Burdale and Wharram Percy showing various degrees of wear. 1) Unworn Burdale knife 244, 2) slight wear on Wharram Percy knife 237, 3) some wear on Wharram Percy knife 307, and 4) Wharram Percy knife 44 with heavy wear. By E. Blakelock.

knives were heavily worn, with another six showing some evidence of wear.

Metallurgical analysis revealed that nine out of the thirteen Wharram Percy knives were butt-welded (type 2). There were also three type 3 knives and a single type 0 knife. Some of the knives with considerable wear (e.g. 134 and 442) may originally have been type 2 knives, but through excessive use, re-sharpening, and heavy wear may have worn through their steel cutting-edges.

A full range of materials were being utilized for the knife backs, including; ferritic iron, low-carbon steels, and phosphoric iron. The majority of the knife backs from Wharram Percy consisted of more than one piece of iron, although it is impossible to determine whether the piled iron backs were deliberate or accidental. Only one knife showed evidence for heat treatment as it clearly had a tempered martensite cutting edge, indicating it was quenched and tempered. Six of the knives had high-carbon structures which consisted of pearlite, while the fine pearlite and bainite structures in some knives suggest that they were cooled quickly.

Burdale

In total 30 knives were recovered during excavations at Burdale. Of these, fourteen were sectioned, including a pivoting knife (Table 4, Fig. 54

Table 3: Summary of thirteen knives from Wharram Percy analysed, showing their manufacturing typology, cutting edge and back microstructures, cutting edge hardness value, average back hardness values, and hardness ranges.

	Type	Cutting Edge			Knife Back		
Knife		Microstructure	HV	HV Range	Microstructure	Avg HV	HV Range
134	3	Ferritic/phosphoric iron	188	172-188	Ferritic/phosphoric iron	175	143-229
159	2	Tempered martensite	450	450-585	Ferritic/phosphoric iron	200	151-219
176	2	Ferrite with pearlite	120	117-125	Phosphoric iron	197	167-220
237	2	Pearlite with ferrite	214	147-214	Ferrite	123	93-141
278	2	Ferrite cutting edge (repair) Fine pearlite or bainite	183 347	138-183 266-524	Ferrite with pearlite	139	131-203
307	0	Ferrite and phosphoric iron	150	152-212	Ferritic/phosphoric iron	187	152-212
308	2	Pearlite	207	193-236	Ferrite	162	125-199
442	3	Pearlite	319	130-319	Ferrite with pearlite/phosphoric iron	150	128-258
472	2	Pearlite	333	131-333	Phosphoric iron	191	166-213
502	2	Pearlite	217	185-264	Ferrite with pearlite	120	85-138
110	2	Phosphoric iron (repair) Pearlite	249 299	196-249 279-380	Phosphoric iron	151	112-187
113	3	Ferrite with pearlite	182	156-205	Phosphoric iron	181	156-205
126	2	Pearlite	285	247-285	Phosphoric iron	232	194-266

/Plate XVII/). X-radiography revealed that 22 knives showed some signs of wear, with thirteen knives having an S-shaped curve (Ottaway 1987); only one knife from Burdale showed signs of heavy wear. In addition, four knives from this assemblage were found bent (Fig. 53).

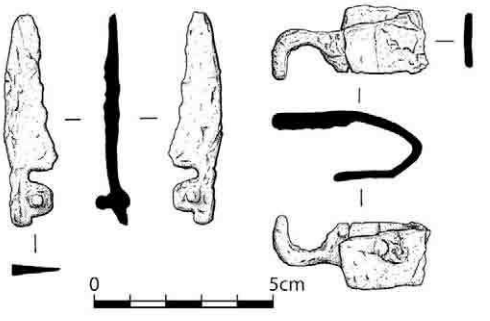

Figure 53: Sketches of the broken pivoting knife 4 (left) and a bent knife 72 (right) from Burdale (Illustration by Daniel Bashford).

The vast majority of knives from Burdale (10 out of 13) are butt-welded (type 2) knives. The other knives consist of two piled knives (type 3) and a knife with steel wrapped around an iron core (type 4). X-radiography of the remaining knives that had not been sampled suggested that there may have been a further ten butt-welded knives.

Seven knives had been heat-treated to create a harder cutting-edge. The remaining knives consisted of three pearlite cutting-edges (0.4–0.7% carbon), which could have been heat-treated, and the others had ferrite with pearlite or phosphoric iron cutting-edges. A range of alloys were used

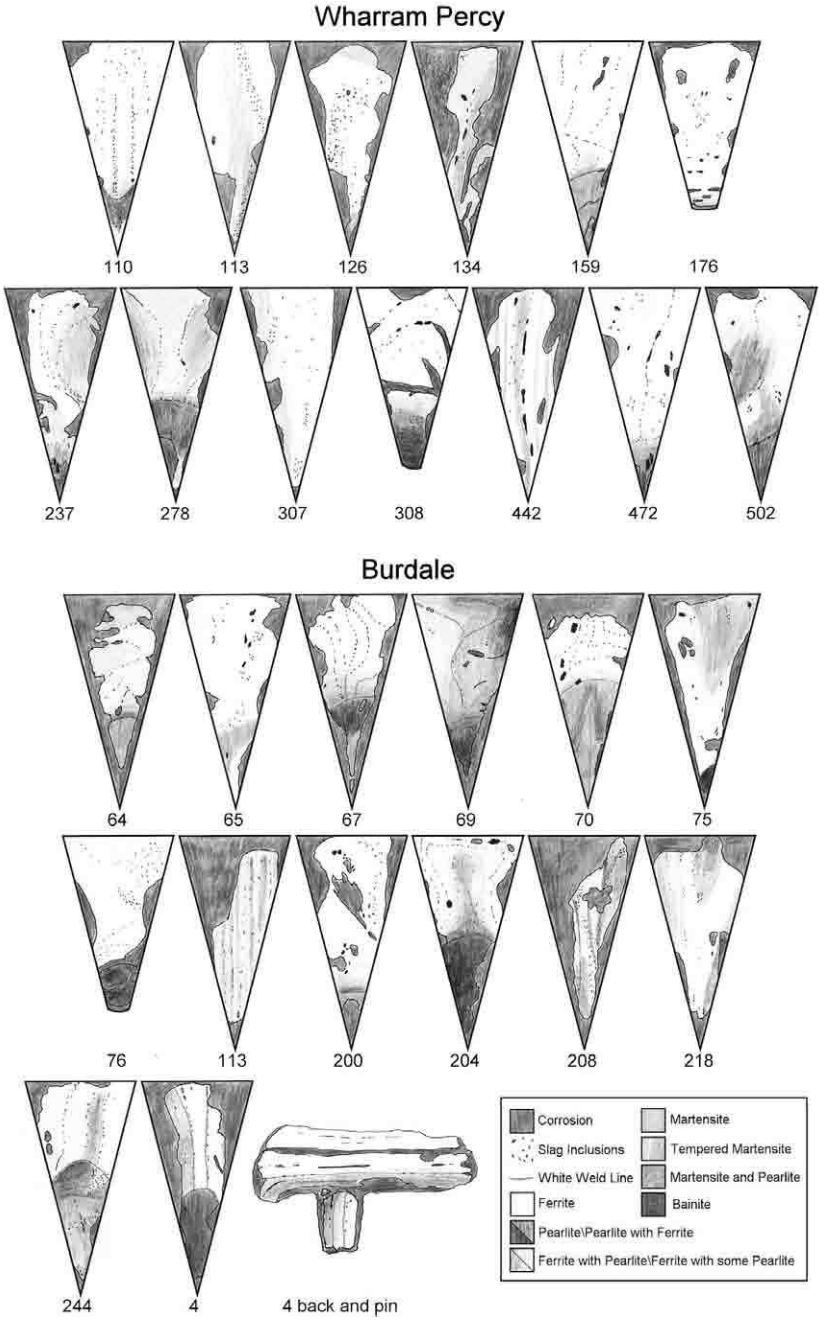

Figure 54: Sketches of the knives from Wharram Percy and Burdale. By E. Blakelock.

for the knife backs, including ferritic iron, phosphoric iron, and low-carbon steels. The backs of many knives consisted of more than one piece, and type, of iron alloy.

The Burdale pivoting knife (Fig. 53) had a clear groove along the knife

Table 4: Summary of fourteen knives from Burdale analysed, showing their manufacturing typology, cutting-edge and back microstructures, cutting-edge hardness value, average back-hardness values, and hardness ranges.

		Cutting Edge			Back		
Knife	Type	Microstructure	HV	HV Range	Microstructure	Avg HV	HV Range
4	2	Bainite/Pearlite	486	386-473	Ferrite with some pearlite	158	107-201
64	2	Tempered Martensite	701	362-701	Ferrite with pearlite/phosphoric iron	130	91-187
65	2	Phosphoric iron (repair) Tempered Martensite	210 578	183-210 473-766	Phosphoric iron	209	161-244
67	2	Tempered Martensite	549	143-549	Ferrite with some pearlite	109	91-137
69	2	Pearlite	257	257-457	Ferrite and pearlite to pearlite	212	183-264
70	2	Tempered Martensite	732	473-766	Ferrite	138	118-161
75	2	Tempered Martensite	549	340-549	Ferrite with pearlite/phosphoric iron	191	103-271
76	2	Pearlite	272	244-321	Ferrite	184	137-221
113	3	Ferrite with pearlite	168	116-176	Ferrite with pearlite	148	116-176
244	2	Tempered Martensite	766	441-927	Ferrite with pearlite (carbides)/phosphoric iron	181	148-210
200	2	Tempered Martensite	671	386-701	Ferritic/phosphoric iron	140	94-168
204	2	Pearlite	441	303-441	Ferrite with pearlite/phosphoric iron	175	140-215
208	3	Ferrite with pearlite	286	196-412	Ferrite with pearlite(carbides)/phosphoric iron	294	196-412
218	4	Tempered Martensite	549	232-549	Ferrite with pearlite(carbides)/phosphoric iron	233	148-303

back, similar to those seen at York (Ottaway 1992). Metallographic analysis revealed it was a type 2 butt-welded knife. The piled iron back ran the full length of the knife, with two separate steel cutting edges welded to either side of the pivot point. The pivoting pin was also made of a piled iron and was pushed through a hole made in the knife blade.

Discussion

Analysis of knives from Wharram Percy and Burdale has confirmed previous findings (Blakelock & McDonnell 2007) that both urban and rural settlements preferred butt-welded (type 2) knives (Table 5, Fig. 55). The differences seen previously between early medieval settlements and cemeteries (Blakelock & McDonnell 2007) do not therefore reflect the difference between urban and rural settlements. The differences between settlement and cemetery knives either represent functional differences (e.g. blades were manufactured specifically for burial) or, more likely, that there is a change in knife technology over time.

The greatest difference between knives from early medieval urban and rural settlements was the heat-treatments applied. Quenching and tempering was the best way to increase the overall hardness and toughness of the knife cutting-edge. In early medieval urban settlements over 75% of knives had heat-treated edges, whereas at Burdale less than 60% were heat-treated and at Wharram Percy only one knife (8%) was heat-treated (Table 6). The extremely poor quality of the Wharram Percy and Burdale steel edges cannot easily be explained, especially since the steel in ten of

Table 5: Summary of the knives from six settlement sites, showing the types of manufacture present and their average hardness value and the range of hardness values. [1](Starley 1999), [2](McDonnell 1987b; McDonnell 1987a), [3](Rogers 1993), [4](Ottaway 1992), and [5](Blakelock & McDonnell 2007).

Sites		Manufacturing Typology and Cutting Edge Data						
		0	1	2	3	4	5	Overall
Wharram Percy 7th-10th	Number	2		9	2			13
	Avg HV	185		281	248			261
	Range HV	171-199		121-524	182-275			121-524
Burdale 7th-9th	Number			11	2	1		14
	Avg HV			533	227	549		474
	Range HV			210-766	168-286	549		168-766
Flixborough [1] 7th-10th	Number	2		11		1		14
	Avg HV	204		556		479		500
	Range HV	139-268		379-650		479		139-650
Six Dials, Hamwic [2] 8th-9th	Number			12			1	13
	Avg HV			430			607	444
	Range HV			153-813			572-642	153-813
Fishergate, York [3] 8th-9th	Number			5				5
	Avg HV			445				445
	Range HV			314-630				314-630
Coppergate, York [4] late 8th - early 10th	Number		2	10		1		13
	Avg HV		503	515		309		496
	Range HV		476-530	270-847		309		270-847
Settlement total	**Number**	4	2	58	4	3	1	72
	Avg HV	195	503	466	238	446	607	437
	Range HV	139-268	232-1288	121-1288	168-286	309-549	441-1283	121-1288
Cemeteries total [5]	**Number**	7	12	7	3	6	8	43
	Avg HV	159	304	686	189	551	255	364
	Range HV	144-208	100-724	258-1000	181-196	433-775	116-650	100-1000

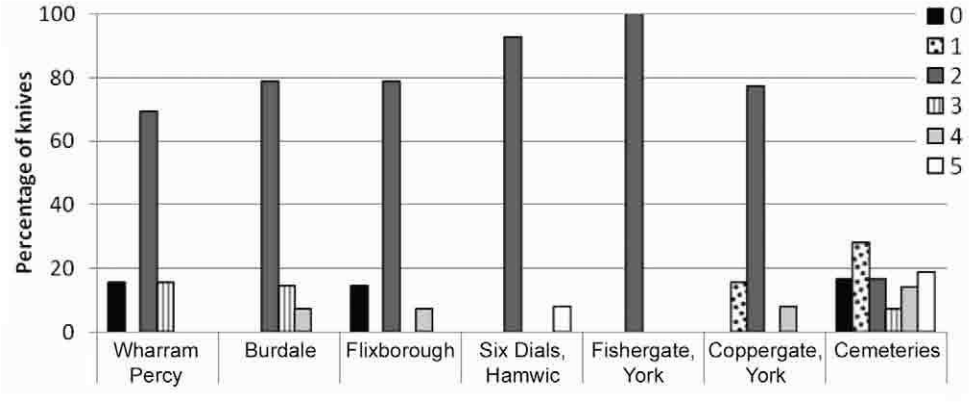

Figure 55: The frequencies of knife manufacturing types at various English sites, including data from Wharram Percy and Burdale (Blakelock & McDonnell 2007).

the untreated knives was of sufficient quality to be heat-treated

There are two possible explanations for the lack of heat-treatment. The first is that the blades had never been hardened, but the other is that the knives had reached the end of their lives and were exposed to excessive heat for extended periods to remove the hardness in preparation for recycling. It is most likely that the reduced proportion of heat-treated knives at Burdale and the lack of them at Wharram Percy indicate that the rural

Table 6: Knife quality based on the average hardness of the cutting-edge, the presence of heat-treated steel and white weld-lines for knives from early medieval sites rural and urban sites. [1](Starley 1999), [2](McDonnell 1987b; McDonnell 1987a), and [3](McDonnell 1992).

Site	No of knives analysed	Average hardness	Number of butt-welded knives	Number of heat treatments	Number of white weld-lines	Number of piled iron backs
Wharram Percy 7^{th}-10^{th}	13	261	9	1	3	9
Burdale 7^{th}-9^{th}	14	474	11	7	7	10
Flixborough 7^{th} -9^{th} 1	6	500	4	5	4	4
Six Dials, Hamwic 8^{th}-9^{th} 2	14	444	11	10	5	5
Coppergate, York late 9^{th}- early 10^{th} 3	13	496	10	11	5	5

smith, although using a good range of materials, may have lacked the ability to carry out the same range of ironworking techniques used by smiths in urban centres. If this was the case, those knives that had been heat-treated were most likely being brought to the site. At Flixborough, another contemporary rural settlement, the quality and number of heat-treated knives was much higher and comparable with the urban sites (Table 6). This is most likely due to the high status of this site, which would therefore have had better access to imported goods or to higher-skilled smiths.

The knives from Wharram Percy and Burdale were constructed of many different alloys (Fig. 56 /Plate XVIII/). The majority of knife backs were either ferritic or phosphoric iron, and most were piled. At Wharram Percy a higher proportion of knife backs consisted of phosphoric iron, while at Burdale *c* 50% were low-carbon steel (ferrite or ferrite with pearlite). Very few knife backs from Burdale or Wharram Percy were constructed of pure ferritic iron, but in York and Hamwic ferritic iron appears to be used more often. This may suggest some degree of choice of alloys, especially since pure ferritic iron may have been less common than phosphoric iron, which was produced by smelting readily available bog ore. In addition to the increase in phosphoric iron, the high frequency of piled iron backs found in rural settlements may be evidence for recycling of iron alloys.

Metallographic analysis of bars and strips of iron from Wharram Percy showed there were no high-quality high-carbon steel bars (pearlite), such as those found in York (Fig. 57 /Plate XVIII/), suggesting that the smithy may not have had easy access to the full range of iron alloys (McDonnell *et al.*, forthcoming). This is supported by the fact that the majority of the Wharram Percy and Burdale knives were constructed using lower-carbon steels and that some iron alloys were used in unconventional ways; there were a large number of steel cutting-edges that had been repaired using

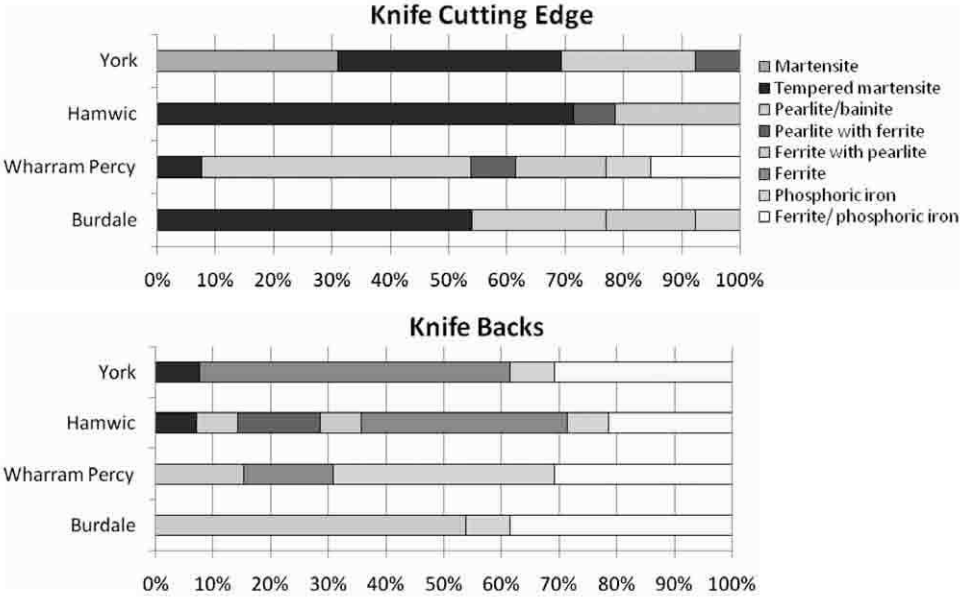

Figure 56: Bar charts showing the percentage of different microstructures and therefore alloy types present in knife cutting-edges and knife backs at each site. By E. Blakelock.

either low-carbon steels or phosphoric iron (Fig. 54, WP110, WP278 and Burdale 65).

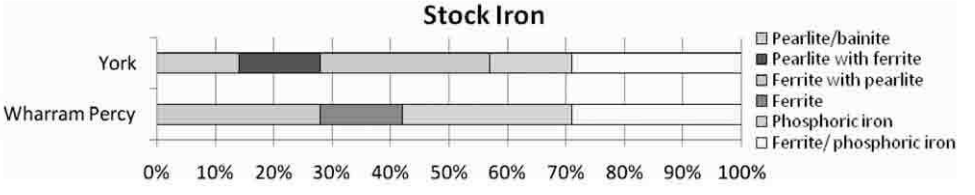

Figure 57: Bar charts showing the percentage of different microstructures and therefore alloy types present in bars found at Coppergate, York, and Wharram Percy. By E. Blakelock.

Most of the knives from Wharram Percy and Burdale showed some signs of wear and many of those from Wharram Percy were heavily worn. To a certain extent the amount of wear present is related to the iron alloy used and any heat-treatments carried out. In addition, the frequency of use and the material that was cut (e.g. meat, bone, wood, or stone) will also affect the amount of wear seen on the knife cutting-edge. Even so, a higher proportion of knives at Wharram Percy and Burdale show signs of wear than those from Coppergate, York.

If a knife became heavily worn, its cutting edge could be repaired rather than discarded. At Wharram Percy four knives were clearly repaired, while

at Burdale two knives showed signs that they had been repaired. This is quite a different pattern to that seen in York and Hamwic, where only one knife from each site had evidence for repair, perhaps owing to their good quality.

During excavations in York and Hamwic a few bent knives were recovered, but at Burdale five (13%) of the knives were bent (Fig. 53) and at Wharram Percy two (12%) knives were found bent. This type of damage could not occur naturally during burial and is unlikely to occur during normal use. Perhaps bending represents ritual destruction prior to discard or, more likely, it is additional evidence for recycling at rural sites. Bending a knife was possibly a method for determining the properties of the metal and therefore allows the smith to determine the alloys present.

Conclusion

In the past the majority of English early medieval metallographic analysis programmes concentrated on either urban centres or cemeteries and, when knives were compared (Blakelock & McDonnell 2007), some clear differences in knife manufacture were seen. This paper addresses these differences by presenting results from the analysis of 27 knives from two rural settlements. Given the relatively small sample size studied so far, these patterns highlighted should be regarded as provisional until further assemblages can be examined.

The first point that emerges from this new study is that the main manufacturing method for both early medieval urban and rural settlements is to butt-weld a steel cutting edge on to a back consisting of ferritic iron, phosphoric iron, piled iron, or occasionally mild steel. The differences between settlements and cemeteries observed during the previous survey (Blakelock & McDonnell 2007) are therefore more likely due to changes in knife technology and manufacturing methods over time, from the cemeteries (5th–7th centuries AD) to the settlements (7th–10th centuries AD). Alternatively, it may be an indication that some knives were created specifically for burial.

Another pattern noted during this analysis is the relative absence of heat-treated knives in rural settlements by comparison with those from urban centres. This, in addition to the absence of some types of stock iron and the many repairs utilizing unusual softer alloys, suggests that many of the better-quality knives from rural settlements were being manufactured elsewhere and were brought to the site. There is also a difference in the alloys used, with more ferritic iron found in knives in urban centres and more phosphoric iron in those from rural settlements. In addition, more

piled iron was found in the rural settlements, and the bent knives found at Burdale and Wharram Percy may suggest that rural settlements were more inclined to recycle iron.

Acknowledgements

We are extremely grateful to the two archaeological projects, Wharram Percy Project and the Yorkshire Wolds Project, for providing us with knives and giving permission for metallographic analysis. Particular thanks go to Ann Clarke and Julian Richards, who supported the project and provided information about each site. We would also like to thank Justine Bayley for reading through an early draft and all those people who have helped and commented on this research.

References

Andrews, P. 1997, *Excavations at Hamwic Volume 2: Excavations at Six Dials* (York: CBA Research Report 109).

Blakelock, E. & McDonnell, G. 2007, 'A Review of the Metallographic Analysis of Early Medieval Knives', *Historical Metallurgy* 41, 40-56.

Hamerow, H. 1999, 'Angles, Saxons and Anglo-Saxons: Rural centres, trade and production', in H.J. Häßler (ed.), *Studien zur Sachsenforschung* 13 (Oldenburg: Isensee).

Hamerow, H. 2002, *Early medieval settlements: the archaeology of rural communities in North-West Europe. 400-900* (Oxford).

Hošek, J. 2003, *Metalografie ve službách archeologie* (Praha)

McDonnell, G. 1987a, *Analysis of Eight Iron Knives and Four Other Tools from Hamwih, Southampton.* Ancient Monuments Laboratory Report 137/87.

McDonnell, G. 1987b, *Metallurgical Analysis of Six Iron Knives from Hamwih, Southampton.* Ancient Monuments Laboratory Report 93/87.

McDonnell, G. 1989, 'Iron and its alloys in the fifth to eleventh centuries AD in England'. *World Archaeology* 20, 373-381.

McDonnell, G. 1992, 'Metallography of the Coppergate knives', in Ottaway, P (ed.), *Anglo-Scandinavian ironwork from 16-22 Coppergate* (London: Archaeology of York 17/6).

McDonnell, G., Blakelock, E. S. & Rubinson, S. R. (Forthcoming), 'The Iron Economy of Saxon Wharram Percy: Modelling the Saxon Iron Working Landscape', in A. Clarke (ed.), *Wharram Percy Middle Saxon Synthesis Volume.*

Ottaway, P. 1987, 'Anglo-Scandinavian knives from 16-22 Coppergate, York', in B.G. Scott, H. Cleere & R.F. Tylecote (eds.), *The crafts of the blacksmith* (Belfast), 83-86.

Ottaway, P. 1992, *Anglo-Scandinavian ironwork from 16-22 Coppergate* (London: Archaeology of York 17/6).

Piaskowski, J. 1961, 'Metallographic investigations of ancient iron objects from the territory between the Oder and the basin of the Vistula river', *Journal of the Iron and Steel Institute* 198, 263-281.

Piaskowski, J. 1987, 'A standardisation procedure for the presentation of the results of metallographic examinations of early iron implements', in B.G. Scott, H. Cleere & R.F. Tylecote (eds.), *The crafts of the blacksmith* (Belfast), 169-178.

Richards, J. D. (In prep), 'An Anglian settlement in Burdale, North Yorkshire'

Rogers, N. S. H. 1993, *Anglian and other finds from 46-54 Fishergate* (London: Archaeology of York 17/9).

Scott, B. G. 1991, *Early Irish Ironworking* (Ulster).

Slater, R. & McDonnell, G. 2002, *Analysis of slag residues from Bestwall, Dorset* (Bradford: University of Bradford Unpublished Report).

Stamper, P. & Croft, R. A. 2000, *The South Manor area* (York).

Starley, D. 1999, *The analysis of Middle Saxon ironwork and ironworking debris from Flixborough, Humberside*, Ancient Monuments Laboratory Report 35/99.

Thompson et al. 1967: Thompson, M. W., Artsikhovskii, A. V. & Kolchin, B. A. 1967, *Novgorod the Great: excavations at the medieval city directed by A.V. Artsikhovsky and B.A. Kolchin.* (London).

Tomtlund, J. E. 1973, 'Metallographic investigation of 13 knives from Helgö', *Antikvarist arkiv* 50, 42-63.

Tylecote, R. F. & Gilmour, B. J. J. 1986, *The metallography of early ferrous edge tools and edged weapons* (Oxford: BAR British Series 155).

Metallography of knives from the medieval village of Hrdlovka and the burial ground of Zlončice, Bohemia

J. Hošek and P. Meduna

The chapter presents results of metallographic examination of 10th–13th century knives from the Bohemian sites of Hrdlovka and Zlončice. Within the framework of the systematization of the description of medieval (or early medieval) sites, Hrdlovka and Zlončice represent two antitheses: the first is a settlement, the second is a burial ground. Their common feature is the topography; both are part of the rural settlement system, without direct spatial links to fortified settlements. Another common feature is their 'commonness,' i.e. the sites do not differ in a number of details from comparable settlements or cemeteries of the period in Bohemia. Since both common and luxury knives have been identified at both these sites, the study clearly indicates that the standard division stronghold = ostentatious and rural site = second-rate is deficient and may be misleading.

Knife - Metallography - Bohemia - Rural settlement - Rural burial ground

Introduction

Radomír Pleiner considered medieval knives a vital source of information about medieval technology from the very beginning, and as early as 1956 he published, together with F. Plzák and O. Quadrat, a study dealing with the manner of the fabrication of early medieval blades, including both knives and swords of Bohemia (Pleiner *et al.* 1956).

The investigation of knives is undoubtedly important for archaeometallurgical and archaeological research because it reflects the technological, organizational, economic, and even aesthetic demands and possibilities of the craftsmen involved (blacksmiths, blade-smiths, cutlers, etc.) and the customers. A knife, as a common everyday tool and nowadays a frequent archaeological find, enables direct comparison of the quality and applied techniques achieved on one type of tool in the context of different social environments. Systematic research into cutlery can therefore gradually enhance our knowledge of the distribution of society and social levels when considering a certain time and territory.

It is therefore not surprising that long-term research into Bohemian medieval knives was also recently put on the research programme of the conservation laboratories of the Institute of Archaeology in Prague, with a view to organizing their systematic archaeometallurgical, restoration, and archaeological survey (Hošek & Šilhová 2006).

Method of investigation

All the examined blades were first treated by restorers (X-ray, detection of organic materials, etc.), then laterally ground,[1] polished (by an adapted polishing machine), etched by 3% nital (Oberhoffer's reagent was also used but not as a general rule), and evaluated according to common standards. Evaluation of the unetched surface had to be omitted. Hardness was measured using the Vickers method on the Zwick 3212 hardness tester only for cutting-edge parts. The blades examined were categorized into three main groups: knives of simple construction, knives of welded construction, and luxury knives of complex welded construction (see also Table 7).

– Hrdlovka

The site of Hrdlovka, located at the foot of the Ore Mountains in northwestern Bohemia, represents, from an archaeological point of view, a long-term village with a continuous evolution from the early Slavic period, from approximately the 7th century up to the mid-13th century. Two successive centres were found in its vicinity – fortified settlements in Zabrušany and Bílina, which during the course of the 9th to 13th centuries gradually acquired the function of regional power centres and undoubtedly also represented trade and craft centres, respectively. However, our knowledge about these sites does not allow us to say anything more. At the turn of the 12th and 13th centuries, the site of Duchcov (with the older name of Hrabišín) was comparable with Zabrušany and Bílina as a trading site. Hence, for at least half a millennium the inhabitants of Hrdlovka could be relatively close to locations with centralized trade (since all three sites are located within 10 km of Hrdlovka) and they could likely acquire various goods via these trade centres, including knives.

Another possibility that must be taken into account is the production of knives directly on the site. The excavation revealed, *inter alia*, a roughly 11th century smithy – an elevated and simple structure, most likely only

[1] Lateral blade polishing is a method adapted for the metallographic examination of Bohemian medieval knives

roofed, with a rectangular base of about 3m×6m. There is a hearth with numerous pieces of slag and several iron items (including one knife), jutting out of the southern side of the structure. The processing of metals was probably carried out continuously on the site (a 10th century crucible with traces of gold has been uncovered there), but clear evidence in the form of processing installations is missing.

The social context of the inhabitants of Hrdlovka can be roughly drawn and completed from the development outlined. Within the framework of early medieval Bohemia, the people were, for their long-term residence in one place, ranked as so-called *heredes*, or *heirs*, i.e. non-liege people governed directly by the king. This status changed sometime between the 11th and late 12th centuries, when the whole area was under the administration of the Hrabišic family. The Hrabišic family gained (it is not known how) control of the settlement of Hrdlovka as a feudatory or property; its inhabitants therefore became more dependent in their status. As late as the beginning of the 13th century, inhabitants of Hrdlovka (the settlement now called Dubany) became serfs of the Cistercian monastery in Osek (a Hrabišic foundation), and after about half-a-century the monastery abolished the settlement and replaced it partly with a field and partly a pond. The inhabitants of the village of Hrdlovka therefore gradually descended the social ladder.

10th century knives (group A, see Fig. 58*, Table 7)*

It is presumed that as many as five knives could have come from the 10th century. Knife 160/91-1 (from structure P41A) was equipped with a striped blade consisting of a back of ordinary iron, a middle rod of high-phosphorus iron, and an unquenched steel edge with decreasing or irregular carbon content. The edge is heavily corroded and isolated islands of metal, denuded near by the cutting edge line, are iron only. Hence an evaluation of the actual heat treatment and quality is impossible. Knife No.73/90-2 from feature G18 also revealed a striped blade, although its blade construction was distinct. The decorative middle rod of high-phosphorus iron was placed between two piled rods consisting of alternate steel and iron layers. The cutting edge was made of steel and quenched. Two other knives come from feature K2. The first one, 168/91-3, was simply made of heterogeneous steel. The cutting edge was just as unquenched and poor in carbon. The second knife (247/91) was, by contrast, an excellent piece provided with a quenched steel cutting edge, which was attached to the middle rod of phosphoric iron by means of a serrated weld. The back of the blade was of ordinary iron. Unfortunately, this fragment of knife comes from the

partially contaminated layers of the structure fill and in consequence we do not have 100% confidence in the dating. Knife 249/91 (K22-14) is most likely from the 10th century structure K4, but could theoretically also be associated with activities that took place in the surroundings of structure K5, dating to the 12th to mid 13th centuries. The dating to the 10th century is *inter alia* supported by a certain similarity with the 10th century knife 160/91-1; both the knives (249/91 and 160/91-1) have striped blades and both were found in similar archaeological context.

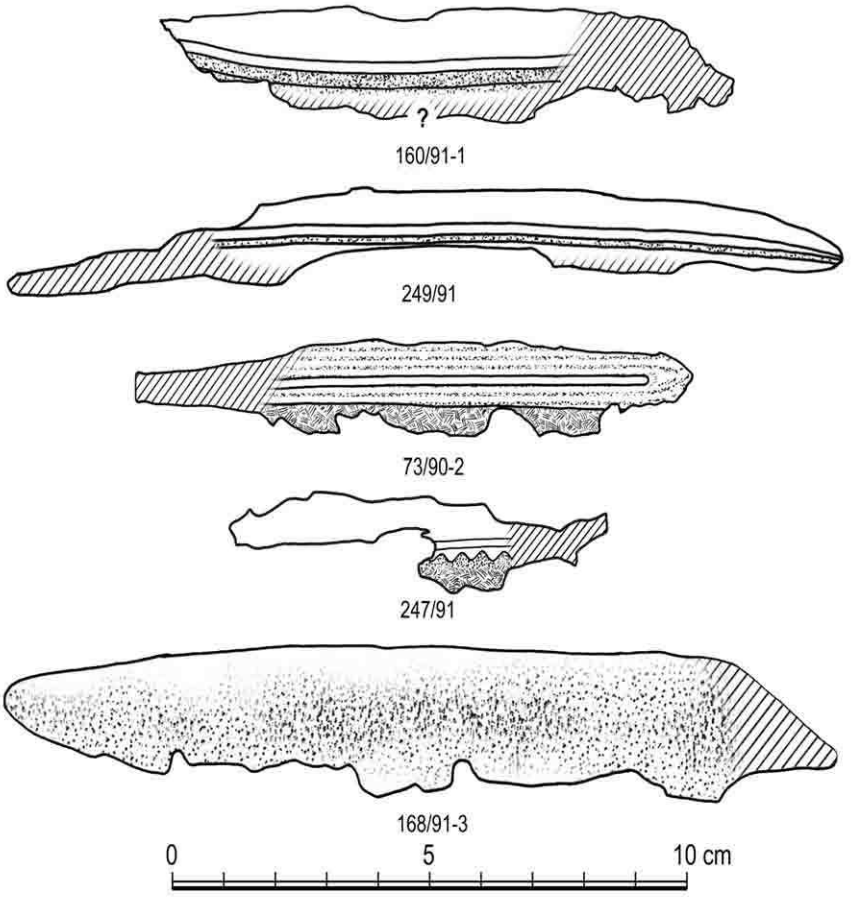

Figure 58: Approximate appearance (revealing the blade construction) of the 10th century knives of Hrdlovka. Drawings by J. Hošek.

11th century to mid 12th century knives (group B, see Fig. 59*, Table 7)*

Seven other knives came from the 11th to mid 12th centuries. Blade

Table 7: Details of metallographic examination.

Site	Knife No.	Dating (century AD)	Feature No.	Blade type	Type of construction		Structures and hardness (HV 0,2) I	II	III	IV	V
village of Hrdlovka	160/91-1	10th	P41A	luxury	striped	D	F+P, F ??	P+F	F_P	F	
	73/90-2	10th	G18	luxury	striped	D	B (510±32), B+F	F, F+B	F_P	F, F+B	
	168/91-3	10th	K2	simple	hetero. steel	A	F+P (190±19)	F+P, P+F			
	247/91	10th	K2	luxury	wavy-welded	G	B (311±28), B+P	F_P	F_P	F	
	249/91	10th		luxury	striped	D	F ??	F+P, P+F	F_P	F	
	90/91	10th - 11th	K12 - K13	luxury	wavy-welded	F	F ??	F_P	F_{P_R} (F+P)		
	160/91-41	10th - 11th	P41D	welded	steel-and-(iron/steel)	E	TM/B (401±63)	F, F+(P)	F_P	F+P	F_P
	83/91 (a)	11th	K14	simple	hetero. steel	A	M+B (451±87)	B+P, F			
	83/91 (b)	11th	K14	welded	iron-and-(iron/steel)	C ?	F	F+P	F, F+P		
	84/91-1	11th	K15	luxury	striped	C	M (424±26), M+B	F_R, F	M		
	232/91-6	11th	P38D	welded	steel-and-iron	C	M (646±25)	F	M, M+F		
	232/91-4	11th to mid 12th	P38F	welded	steel-and-iron	B	M (551±76)	F			
	33/89-2	1st half of 12th	A5/89	luxury	wavy-welded	G	M (716±94)	F_P	M+F, F+P	F	
	31/89-1	1st half of 12th	A4/89	luxury	wavy-welded	H	B (278±41)	F_P	F+P	F	B
	233/91	12th	P31	welded	steel-and-iron	E	M (404±19), M+F	F	F+P, P+F, M	F, F_P	M
	107/90-2	2nd half of 12th	B3	luxury	wavy-welded	F ?	M (809±17)	F, F+(P)			
	604/92-13	12th to mid 13th	51/92	simple	iron	A	F				
	287/91-29	12th to mid 13th	P61B	luxury	wavy-welded	F	B (295±11)	F_P	F, F_P		
	107/90-3	2nd half of 12th	B3	welded	steel-and-iron	B	B, F	F, F_R, F+(P)			
	108/90-3	12th to mid 13th	B13A	welded	steel-and-iron	B	M (560±77)	F_P			
burial-ground of Zločičice	28	11th	grave 2	welded	steel-and-iron	B	M (519±13)	F_P (197±14)			
	22	11th	grave 23	welded	steel-and-iron	B	B (333±27)	F (134±4)			
	23	11th	grave 25	luxury	pattern-welded	I	M (502±35)	F, F+P	M / F_P	F, F+P	F_P

Structures: F...ferrite; F_P...phosphorus-rich ferrite; P...pearlite, P_G...globular pearlite; B...bainite, M...martensite; TM...tempered martesite (*A*)...*A* in traces; *A/B* ...*A* or *B*; *A + B* ...mixture of *A* and *B* (*A* prevails); *A, B* ... *A* and *B* in discrete zones.
Hardness: Vicker's method, load 200g ... (mean value ± standard deviation)

fragment 90/91 (found between structures K12 and K13) revealed a serrated weld between its cutting edge and the central strip of phosphoric iron, while the back of the blade was also phosphoric iron. The edge was heavily corroded, but the preserved metallic islands found nearest the cutting-edge line were only of ferritic iron. Though the knife was a luxury item, the materials for its production were not selected carefully and the edge was of rather inferior quality. Knife 84/91-1 (from structure K15) has both a cutting-edge and a back of quenched steel, while the central strip is partially of phosphoric iron. This construction can be considered to be one of the variants of striped blades (like knife 677 from Budeč, for instance) and the blade is classified as excellent and a luxury item. Only simply made knives were found in the structure K14. The first one (83/91(a)) was made entirely of steel and quenched, whilst the second (83/91(b)) was entirely of iron. Neither knife 232/91-4 nor 232/91-6 from structure P38 (interpreted as a smithy) ranks as a luxury item. Blade 232/91-4 is of a standard construction (a cutting-edge of steel, iron back) and blade 232/91-6 is even above standard, with both an edge and a back of steel; the mid-strip is iron (but it is not a case of a luxury striped blade). The cutting edges of both knives were perfectly quenched and their utility was excellent. Blade 160/91-41 (structure P41D) shows curious striping, with considerable irregularity of the pattern. The striping dimly resembles the look of luxury striped knives, but the blade was most likely made of scrap or unsorted iron. The cutting edge was quenched steel.

12th century to mid 13th century knives (group C, see Fig. 60*, Table 7)*

The last eight knives can be dated from the 12th to mid 13th centuries. Half of them revealed serrated welds and various constructional schemes in the blade-backs (all the blades, of course, have a central strip of phosphoric iron). Blade fragment 287/91-29 (structure P61B) was provided with only a medium-quality cutting edge (although hardened) and an iron back. Fragment 33/89-2 (feature A5) has in addition a strip of steel above the phosphoric-iron part, while the back itself was ordinary iron. This blade revealed an interesting appearance as well as a very hard cutting-edge, and without doubt ranks among the best knives from Hrdlovka. Blade 31/89-1 (feature A4) was of a most complex and interesting construction (see Fig. 60). Nonetheless, neither the cutting edge nor the back of the blade have enough carbon to achieve a suitable hardness by quenching. Hence, from the point of view of utility value the blade was of rather mediocre quality. On the other hand, blade 107/90-2 (from well B3) was provided with the hardest cutting-edge (around 800 HV0.1) among all the Hrdlovka knives.

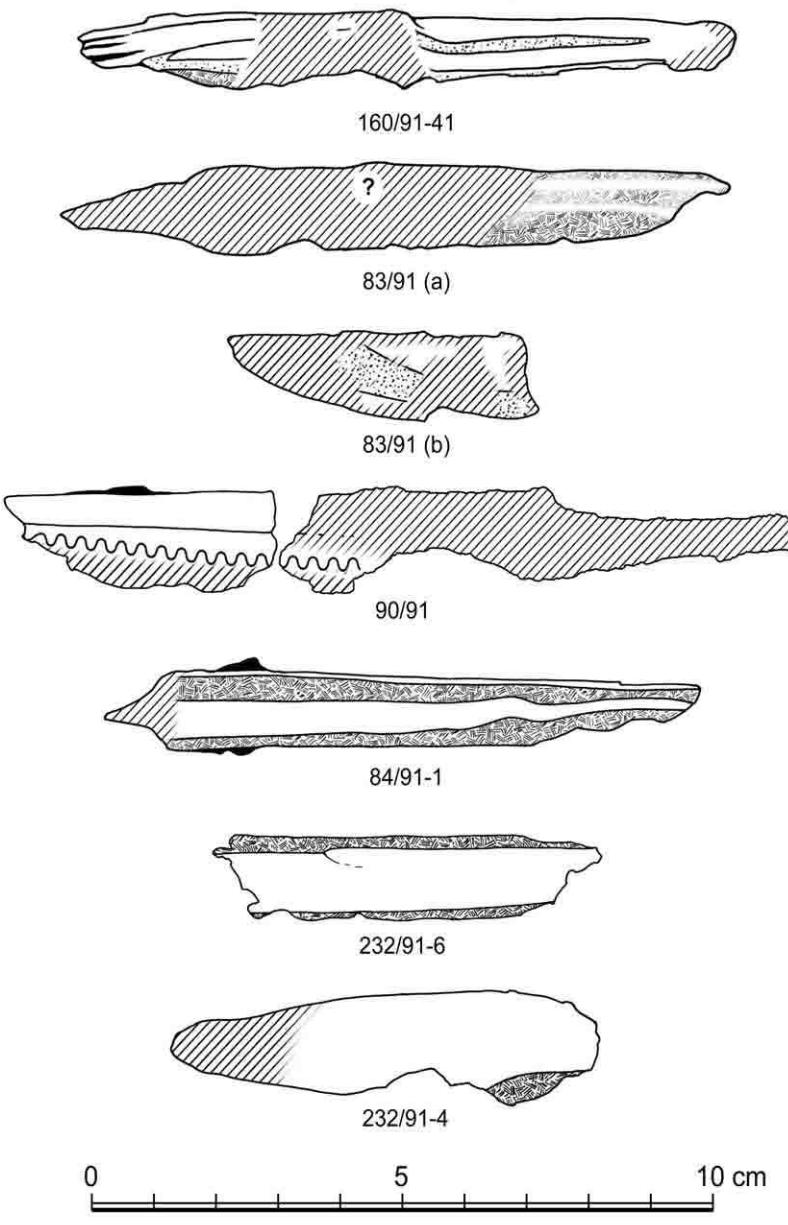

Figure 59: Approximate appearance (revealing the blade construction) of the 11th century to mid 12th century knives from Hrdlovka. Drawings by J. Hošek.

Because one of the object's sides revealed a serrated blade construction whilst the other is only iron (most likely a part of the casing was turned 9° against the blade), we interpret the find as a razor. There were two knives of standard construction, i.e. with a back of iron and an edge of

steel: 107/90-3 (structure B3) and 108/90-3 (feature B13A). The quality of the first one was rather average, but the second was an excellent piece. Knife 223/91 (feature P31) is interesting, but it was hard to say if it was an intentionally made blade (three strips of quenched steel – in the cutting edge, in the middle, and in the back of the blade). In any case, this good-quality blade has none of the features of striped blades and hence it does not rank as a luxury item. Blade-fragment 604/92-13 (structure 51/92) does not have a carbonized steel cutting edge (although we did not find one the edge might have been entirely worn-out or broken away). However, such 'iron' blades were as a rule actually made only of iron.

– Zlončice

The site of Zlončice is a rural burial ground. The cemetery (which was completely excavated) consists of eight graves; such a small number represents rather an exception in comparison with contemporary necropolises. According to a preliminary anthropological determination, the interred were both men and women of various ages and represent the 'common' population. The grave arrangements (a lining of stone and wood) suggest that the burial ground was used mainly during the course of the 11th century (more precise dating is impossible because of the poor condition of the grave goods). There is no excavated settlement related to this burial ground; however, on the basis of analogies and local topography it can be expected with certainty to be at a distance of several hundred metres. If we consider (as in the case of the Hrdlovka site) the distance to the nearest contemporary residential centres, then perhaps the stronghold of Levý Hradec, or rather Klecany (for the period), both located approximately 6km from Zlončice, should also be taken into account. The centre of Prague is roughly 15km away. A certain exclusivity of Zlončice consists in a possibility to place the site more precisely in the social context of the 11th century. The foundation charter of the Stará Boleslav chapter mentions a group of inhabitants known as *custodes ecclesiae* (i.e. guardians of the church) who were, around the mid-11th century, also donated from Zlončice. The relevant passage reads: *Znoicicih Gormusa sum filiis Vitas, Bogdan, Milowan, Mirota, black, cum filio Crazota bargain, Dragota.* Verbatim translation and interpretation suggests several variants for expressing family relationships (e.g. 'Gormusa with five sons, Necta with one and another Dragota') and raises the question of whether the excavated cemetery is not a burial ground for a single family. In any case, the determination of the population itself is more important for our considerations. The people were serfs of the ruler (Břetislav I), who donated themselves to the chapter, and they were obliged to guard the chapter sanctuary.

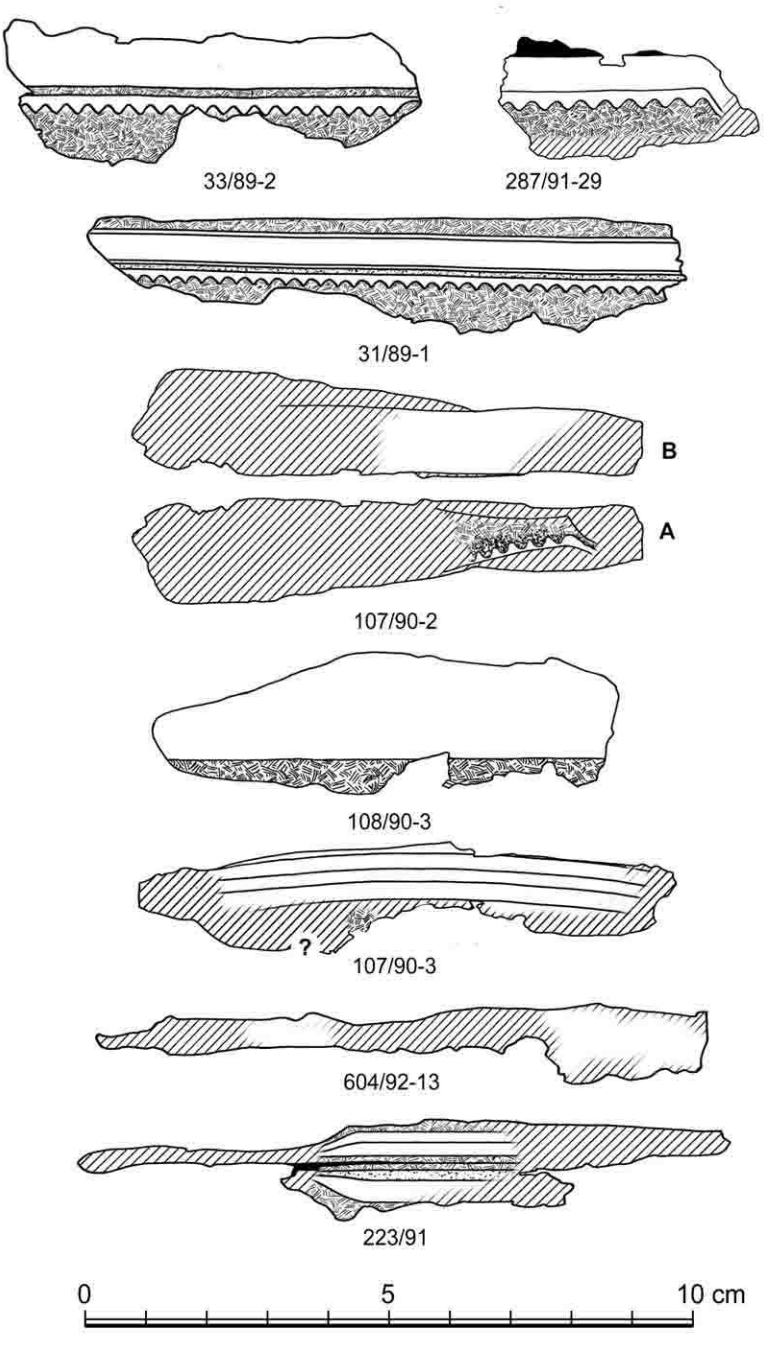

Figure 60: Approximate appearance (revealing the blade construction) of the 12th century to mid 13th century knives from Hrdlovka. Drawings by J. Hošek.

Whether they had any other guard duties before the donation is not entirely clear, but it is quite possible (it is not without interest that in the

14th and 15th centuries royal feudatories are still registered in this area, and so in principle there is a similar rank of society). The inhabitants of Zlončice thus had access to the acropolis and to the charter district in Stará Boleslav in the given period. The guardians of the church probably had a certain autonomy: their rank was higher and the nature of their service, of course, required at least basic arms and armour.

Three out of the four knives excavated in Zlončice could be examined metallographically (see Fig. 61, Table 7). Knives 28 (grave 2) and 22 (grave 23) were high-quality products of standard welded construction consisting of a cutting edge of quenched steel and a back of iron. Although very similar, the blades are not entirely identical; the first one (28) has a harder edge and its blade was provided with a back of phosphoric iron, which favourably influenced its appearance. We are not able to recognize whether this scheme is deliberate, but even if it was, the knife would be only of a high standard. Knife 24 (grave 25) was a high-quality, luxury blade. Its back revealed a pattern-welded core placed between two iron strips, and the back-edge was of phosphoric iron. The knife was an excellent and valuable product provided with hard steel cutting edge (Fig. 62 /Plate XIX/).

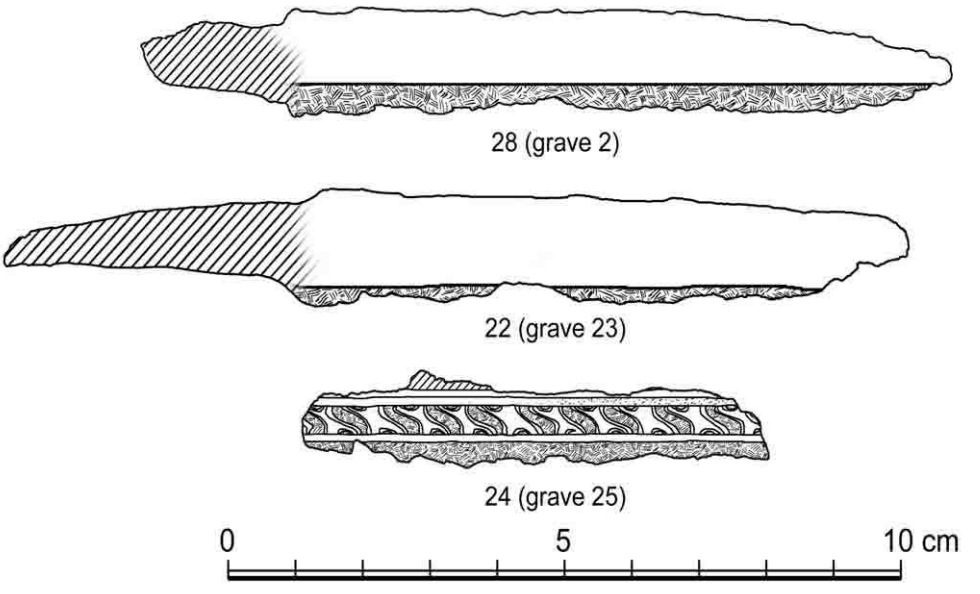

Figure 61: Approximate appearance (revealing the blade construction) of the 11th century knives from Zlončice. Drawings by J. Hošek.

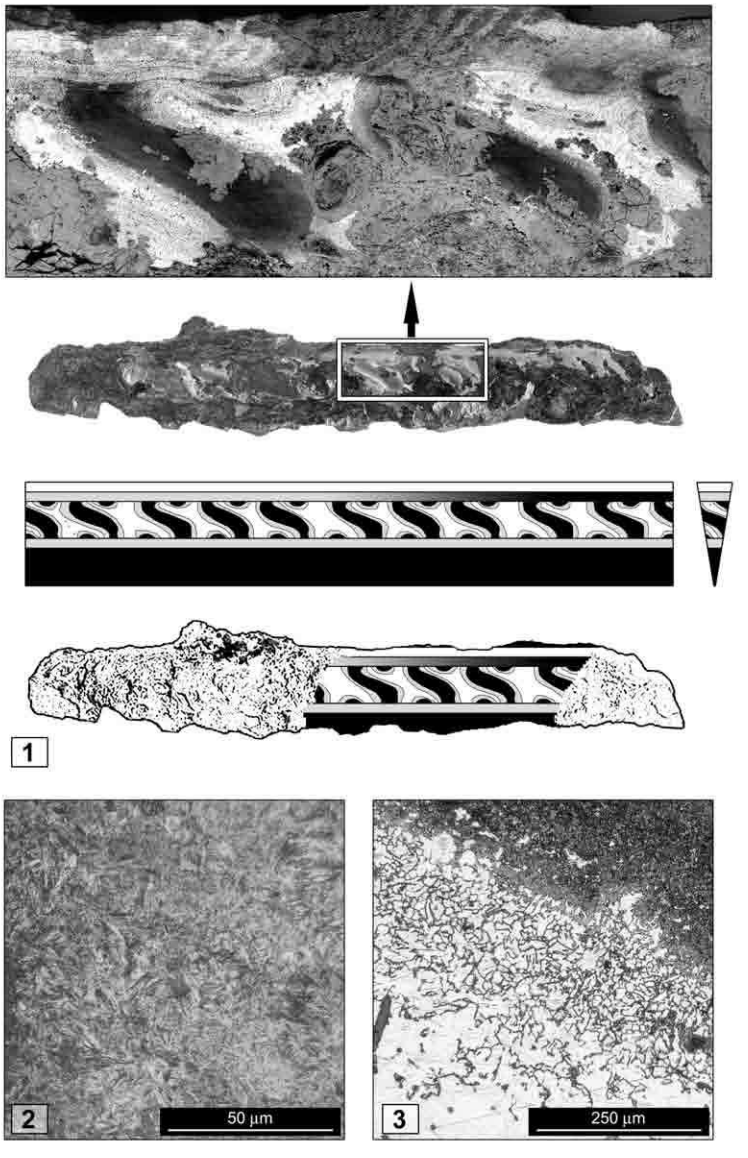

Figure 62: Zlončice, *c* 11th century; pattern-welded knife 24 (grave 25); 1: detail of the lateral polishing, which revealed a patterned core; 2: martensitic structure of the cutting edge; 3: structures of the pattern-welding; etched with nital. Photographs by J. Hošek.

Discussion

Hrdlovka is, from the viewpoint of archaeometallurgical research, an undoubtedly interesting site as it gives us an opportunity to study the facilities of a rural residential site of the early medieval period, which seems to be the crucial stage for the development of Bohemian and Moravian

knife-blade smithing techniques. The research revealed that as much as half of the examined Hrdlovka knives were of a complex construction, intended to enhance their appearance and attractiveness, and only a few of them appeared to be simple forgings. The small sizes of the groups prevent us from reliably estimating the percentage of the distributions of the presented knife-types, but we can work with the ranges determined by binomial tests. As Fig. 63 shows, the estimated ranges of the genuine probability of luxury knife occurrence allow us to think of a relatively general distribution of these knives. This is rather surprising (at least from the point of view of the research conducted until now into Bohemian and Moravian medieval cutlery), and also taking into consideration the rural features of the settlements. What is also surprising is the number of collected luxury blades from the 10th and 11th centuries. Examined assemblages from Bohemian strongholds (such as Budeč, Stará Boleslav, Malín, etc.) have led us to believe up to now that the appearance of luxury knives was associated almost exclusively with early medieval centres of power and/or with a more highly ranked part of society. What is also interesting is the fact that the appearance of luxury knives does not reflect the gradual reduction of the independence of the people during the period. Outstanding information about the 'use' of some of the luxury knives has been gained from associated archaeological contexts. Knife 160/91-1 (P41A), which was found alongside a fragment of the base of a vessel bearing the mark of a cross, and knife 249/91 (structure K22-14), were, in the 10th century, most likely deliberately deposited nearby the house corners. In the course of the late 10th to mid-12th centuries, knife 90/91, equipped with a luxury serrated blade, was inserted in the bottom of a posthole situated between features K12 and K13. Another serrated knife fragment, 287/91-29, originating from the 12th to mid-13th centuries, was discovered near a corner of house P61B, whose several circuit postholes contained wires or lockrings of bronze. The knife itself was also found in a posthole, but it is uncertain if the post belonged to the house. We can see that all of these knives, representing the most beautiful (though not most employable) pieces that could be found at Hrdlovka, more or less resemble sacrificed objects, and their use in everyday life is therefore questionable.

Two of the knives from Zlončice, from graves 2 and 23, are of standard construction but a fragment found in grave 25 revealed a pattern-welded blade with a hard cutting edge and is an excellent luxury piece. Despite the rural features of the graveyard, the discovery of such a luxury knife is not surprising given the social rank of the inhabitants of Zlončice and their close links with the stronghold of Stará Boleslav. The relatively numerous sets of Stará Boleslav knives also revealed, *inter alia*, three pattern-welded knives, at least two of which could be contemporary with the find from

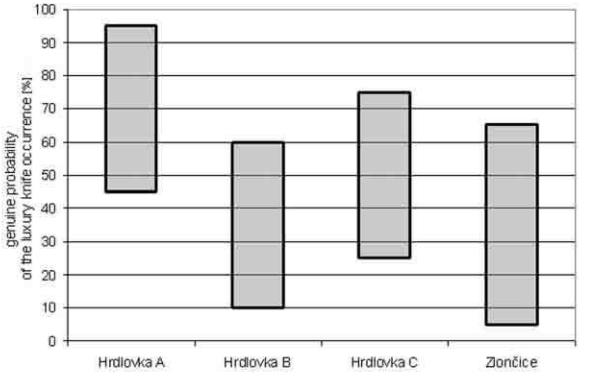

Figure 63: Estimated ranges of the genuine probability of luxury knife occurrence in single periods and sites (based on binomial tests). By J. Hošek.

Zločice (Boháčová & Hošek 2009, Tab. 5, 380). In relation to the context, fifteen Bohemian pattern-welded knives overall have been published to date (see Table 8), but only two of them came from graves (one knife from Lahovice and one from Malín; see Pleiner 1979; Hošek *et al.* 2007; Velímský *et al.* 2007). Whilst dating of the graves did not bring any noteworthy information (a range from the 10th century to the 13th century), the fact that only male graves contained such knives is remarkable. What is also noticeable is the fact that the graves were found on rural burial grounds. In general, factors such as published dating and archaeological context have not yet revealed any effect on, nor any mutual interaction with, the numbers of recognized (excavated and researched) patterned Bohemian knives. What is interesting is the question of whether any of these knives were manufactured in Bohemia. The sparse collected data do not allow any meaningful analysis to answer this question; however, taking into account the site of Sekanka (see Pleiner 1982), and also the numbers of striped and serrated blades discovered in the Czech Republic by current research, it also seems that the manufacture of luxury knives (provided with pattern-welded, serrated or striped blades) could have been a nascent tradition in Bohemia as early as the 10th century and continuing up to the 13th or (perhaps) the 14th century.

Conclusion

Although the studied sites of Hrdlovka and Zlončice differ in their function (the former is a settlement, the latter a burial ground),they have common features such as belonging to the rural settlement system with-

Table 8: Overview of published Bohemian knives.

Identification of knife	Site	Dating	Type of site	Archaeological context	Note	Cutting edge structure	Hardness of the cutting edge	Published by
8/65-2420 (423)	Mutějovice	12th	rural smithery	house 8		TM	579-658 mHV	Pleiner 1969, 561, Fig. 17 and 18
46/58-186 (274)	Lahovice	early to mid 10th	rural burial-ground	male grave (32/58)		M (B)	482-616 mHV	Pleiner 1979, 247, Tab. IV-VI (357-359)
346 (215)	Sekanka	late 13th	monastery town	pit E-A2		M	600 mHV	Pleiner 1982, 270, T43
345 (216)	Sekanka	late 13th	monastery town	pit E-A2		M	860-900 mHV	Pleiner 1982, 270, T44
76 (227)	Sekanka	late 13th	monastery town	structure IV		M	550-900 mHV	Pleiner 1982, 271, T46
(235)	Sekanka	late 13th	monastery town	structure IV		M	850-1150 mHV	Pleiner 1982, 272, T48
705 (249)	Sekanka	late 13th	monastery town	house 11		M	600-1200 mHV	Pleiner 1982, 273, T51
710 (260)	Sekanka	late 13th	monastery town	house 11		B?	360-400 mHV	Pleiner 1982, 273, T51
706 (251)	Sekanka	late 13th	monastery town	house 11		M	660-800 mHV	Pleiner 1982, 273, T51
13471-578/84	Přerov	10th/11th	stronghold	(from Horní náměstí č.p. 8 and 9)	two patterned rods	F	226±6 HV0.3	Procházka et al. 2003,388-389,Obr. 1-3
4198 (749)	Stará Boleslav	9/10th-11th	stronghold	XXXIV B/95 (stronghold acropolis)		B	323±28 HV0.2	Hošek 2003,280, 282:Fig.1, 286:Fig.4, 283: Tab.2
3166 (747)	Stará Boleslav	9/10th-11th	stronghold	XVI/95 (stronghold bailey)		P	202-261 HV0.2	Hošek 2003, 279, 282:Fig.1, 283: Tab.2
2964	Stará Boleslav	12th	stronghold	2-XVI-XVII (stronghold bailey)	with serrated weld	M-B	417±76 HV0.2	Boháčová and Hošek 2009, 380:Tab.5, 378:Obr.5
-	Olomouc	late 13th	town	(from Horní náměstí)	with serrated weld	-	-	Sága Moravských Přemyslovců 2006, 233
1318/03	Malín	early to mid 13th	rural site	male grave 1/03 (IV/03)	with serrated weld	M	795±71 HV0.1	Velímský et al. 2007, 398, 397: Fig.9
/24/	Zloučice	ca 11th	rural burial-ground	male grave 25		M	502±35 HV0.2	

out direct spatial links to fortified settlements, and both in various details not differing from comparable settlements or cemeteries from the period in Bohemia.

Research carried out on the excavated knives revealed, in both cases, the presence of various blade types, including luxury, intricately structured blades of an impressive appearance. Owing to the small number of sets examined, we cannot determine the actual rarity of these luxury knives; we cannot, in fact, definitively assert that they were rare.

In any case, sites such as Hrdlovka, Zlončice, Lahovice, and others provide clear evidence that as early as the 10th or 11th century, people from settlements scattered over the countryside were also able to acquire valuable knives, in ways that we do not know; this indicates that the standard division *stronghold = ostentatious* and *rural site = second-rate*, etc. is deficient.

Acknowledgement

The authors are grateful to the Grant Agency of the AS CR, which supported this work in the framework of the project No. IAA800020603.

References

Hošek, J. & Šilhová, A. 2006, 'Metalograficko-restaurátorské průzkumy raně středověkých nožů', *Archeologické rozhledy* 58 (1), 59-75.

Hošek, J. 2003, 'Metallographic examinations of the 10th to 12th centuries knives from the Premyslid stronghold at Stara Boleslav (Bohemia)', in *Archaeometallurgy in Europe* vol. 1, (Milan). 219-228.

Hošek, J. et al. 2009: Hošek, J., Velímský, F., Šilhová, A. & Ottenwelter, E. 2009, 'Metallography of medieval knives from Malín (Bohemia)', in *Archaeometallurgy in Europe* 2007 (Milan), 272-281.

Pleiner, R. 1969, 'Středověké sídliště s kovárnami u Mutějovic', *Památky archeologické* 60, 533 –571.

Pleiner, R. 1979, 'K vývoji slovanské nožířské techniky v Čechách', *Archeologické rozhledy* 31 (3), 245-256, 354-360.

Pleiner, R. 1982, 'Techniky kovářské výroby', in M. Richter, *Hradišťko u Davle* (Praha), 268-300.

Pleiner, R. 1993, 'Die Technologie der Messerherstellung in der Früh-

mittelalterlichen Fürstenburg von Budeč, Böhmen', *Památky Archeologické* 84, 69-92.

Pleiner, R. et al. 1956: Pleiner R., Plzák F. & Quadrat O. 1956, 'Poznámky k výrobní technice staroslovanských čepelí'. *Památky archeologické* 47, 314-334.

Procházka, R. et al. 2003: Procházka, R., Ustohal, V. & Doležal, P. 2003, 'Materiálová analýza raně středověkých kovových předmětů z Přerova', *Pravěk NR* 13, 387-404.

Sága moravských Přemyslovců: život na Moravě od XI. do počátku XIV. století, Sborník a katalog výstavy 2006 (Olomouc, Brno).

Velímský, F. et al. 2007: Velímský, F., Hošek, J. & Stránská, P. 2007, '"Quod me nutrit me destruit" Malín – výzkum hrobu dvou mladých bojovníků', in *Środowisko pośmiertne człowieka – Funeralia Lednickie* 9 (Poznań), 389-402.

Technological traditions in the craft of the blacksmith in old Russian Shestovitsa

G.A. Voznesenskaya

The technical culture of the Slavic and Old Russian peoples in south-eastern Europe in the field of blacksmithing was inherited from Scythian metalworking, with certain influences from Celtic technology, most notably in the Late Roman period. Many blacksmith artefacts found in the village of Shestovitsa, near Chernigov, were subjected to metallographic investigation. The nature of the trade and crafts of the settlement is demonstrated by numerous finds of tools, finished products, and waste materials from iron smelting, forging, and pottery making from all parts of the site. About 55% of the 195 knives from the settlement and burial mounds of Old Russian Shestovitsa were made according to the Slavic productive tradition and the remaining 45% in the Scandinavian tradition. It can be said that improved metalworking technologies invented by the craftsmen of the ancient world spread and developed in the Old Russian state thanks largely to the influence of the Scandinavian craft traditions.

Blacksmith craft - History of archaeometallography - Metallographic research - Scientific literature

By the end of the 20th century scientists in Moscow and Kiev studying the origins and development of European ironworking were working together on the technological traditions in the craft of the blacksmith in the northern and southern regions of Russia (Voznesenskaya & Kovalenko 1985, 95–109; Rozanova 1988, 57–59; Voznesenskaya *et al.* 1996, 80–124; Rozanova 1997, 265–295; Voznesenskaya 1999, 117–126).

It is evident that simple techniques of iron processing prevailed in the craft of the blacksmiths working in the towns of southern Russia: the products were made from solid iron or steel and the earlier technological tradition of finished product and blank carburization continued. The culture of the Slavic and Old Russian blacksmiths in south-east Europe was based on that of the Scythian metalworkers, with some influences from Celtic technology, particularly in the Late Roman period (Voznesenskaya 1995, 47–52; Voznesenskaya *et al.* 1996, 17–23, 42–60).

In the towns of northern Russia in the 10th–11th centuries the ironworking technology was based on triple welding.[2] In the centuries that followed this was replaced by the technique of welding steel cutting-edges on iron cores for various implements. This process is most clearly manifested in the blacksmith technology of Novgorod the Great and the towns of the Novgorod region (Rozanova 1989, 73–76: Zavyalov & Rozanova 1990, 154–172).

The analysis of smithing products resulting from the excavations of north European trading and production centres and the associated cemeteries shows that in the 7th–11th centuries it was the technology of welded structures, and triple welding in particular, that dominated there (Tomtlund 1973, 42–63; Pleiner 1983, 63–92; Arrhenius 1989, 79–92; Lyngstrom 1995, 81).

Researchers associate the adoption of triple welding by the Old Russian blacksmiths with the coming of Scandinavian Vikings to medieval Russia, because knives with triple-welded blades first appeared in settlements where a Scandinavian ethnic component is very evident. These were mostly proto-urban settlements that developed in Russia and the neighbouring trading towns of Baltic Pomerania resulting from the rapid development of trans-European trade relationships in the 9th–10th centuries such as the Sarskoye settlement (Kolchin 1953, 221, 222), the Gnezdovo complex (Rozanova & Pushkina 2001, 77–82), Krutik (Rozanova 1991, 166–181), and Gorodok on the Lovat' (Voznesenskaya 2000, 18–28).

The earliest triple-welded knives in eastern Europe originate from Staraya Ladoga, where this technological process was observed to be the basic one for blades from deposits dating back to the late 7th–9th centuries (Rozanova 1994, 176).

The researchers studying the problems of development of the Old Russian towns agree that the open settlements of merchants and craftsmen attracted multi-ethnic peoples involved in distant trade, military campaigns, and crafts (Tolochko 1989, 50–59; Nosov 1993, 59–78; Nosov 2002, 5–42).

Among the craft activities practised at these settlements ironworking is very strongly in evidence, and what are clearly alien techniques can be observed (beginning with triple-welding) in its production traditions. This can be explained as deriving from the direct influence of Scandinavian production traditions that went on to establish the fundamental smithing traditions in northern Russia.

In the last decade the systematic excavations of the Old Russian settlement at the village of Shestovitsa, 18km from Chernigov down the Desna

[2] This term is used in the present paper for the technique of heating and hammer-forging three strips of metal for further shaping to produce knife blanks. Ed.

River have produced many smithing objects that have been investigated metallographically.

The Shestovitsa site belongs to the group of proto-urban trading and craft centres situated on the most important water routes. The excavators of the site believe that the small unit of professional fighting men who lived there was multi-ethnic in character, with a considerable Scandinavian component. The unit evidently controlled the Kievan princes, Chernigov, and the main water route along the left bank of the Dnepr. The Shestovitsa settlement functioned from the late 9th to early 11th centuries, the peak of its power dating back to the 10th century (Kovalenko 2001, 190; Kovalenko *et al.* 2003, 51–67).

Proof of the trading and craft character of the settlement comes from the numerous finds of tools, finished products, and waste materials from iron smelting, smithing, and pottery-making from all parts of the site. The objective of the present work is the investigation of the technology and general technical culture of ironworking production in Shestovitsa. In light of the special character of the settlement we shall try to determine the origins of local technological traditions.

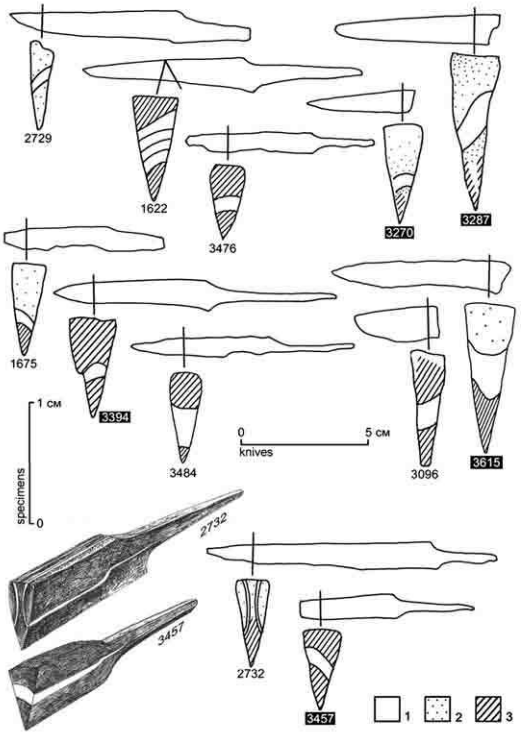

Figure 64: Technological schemes of knives from southern Russian sites with inserts of hard high-phophorus ferrite (3270, 3287, 3394, 3457, and 3615 are from Shestovitsa). Key: 1 – iron, 2 – steel, 3 – heat-treated steel. Drawings by G. Voznesenskaya.

The technological characteristics of the Shestovitsa blacksmiths' production is the result of the study of over 300 iron objects. These are high-quality forged items obtained from excavations of the trading quarter within the main site, some other suburbs, and the *kurgan* cemetery (Voznesenskaya 2005, 101–113; Voznesenskaya 2006, 39–44). Below are the results of the analytical investigation of more than 195 specimens of household knives studied so far. These are the best examples for documenting ironworking techniques and technology. The material makes it possible to reveal both the stability of technological traditions and the insertion of alien technical innovations in local production activity.

It is possible to identify five technological processes for knife production in Shestovitsa in the 10th century:

1. Knives with solid iron blades (30 specimens). They are shaped by blacksmith forging without any actions intended to improve the quality of the cutting-edge. Ordinary bloomery iron is used, the microhardness of ferrite ranging from 170 to 221 kg/mm^2. Some of the blades of this group were forged of hard bloomery iron with hardness rising to 322–421kg/mm^2; they are notable for their coarse microstructure which unquestionably indicates the use of hard iron with high phosphorus contents as the raw material.

2. Knives with solid steel blade (69 specimens). The raw material for these knives was bloomery steel with uneven carbon content and distribution. The majority of the blades shows traces of heat-treatment in the form of martensitic and martensito-troostite structures. Sorbitic and globular pearlite structures may point to certain methods of heat-treatment or tempering, when the object was plunged into the hearth. The blades of some knives were forged from hard-steel blanks that had been uniformly tempered, as shown by their homogeneous structures and high cutting-edge microhardness.

3. Knives with carburized cutting-edges (8 specimens). All these knives were made by a single process: homogeneous carburization of the cutting-edge followed by hardening. Only one carburized knife has an annealed cutting-edge. It should be pointed out that all the knives with carburized cutting-edges were made of ordinary soft iron (microhardness *c* 170–206 kg/mm^2).

4. Knives with triple-welded blades (71 specimens). These knives were made by the traditional process of triple-welding: in the centre there is a core of high-carbon steel jutting out to form the cutting-edge, with iron plates on either side. The blades are usually hardened. This group of knives also includes some items made by deep welding a steel cutting-edge into an iron core followed by heat treatment.

This is usually considered to be transitional between triple- welding and the use of a welded-on steel blade.

5. The knives with triple-welded blades show two characteristic features. First, their shape puts them in the category of narrow-bladed knives with straight and thick backs, accurate shouldering, and long narrow tangs (type IV of R.S. Minasyan's classification). This researcher has traced their Scandinavian origin. The knives in question appeared in eastern Europe in the last quarter of the 1st millennium AD; it is of importance that the knives of group IV are known all over the territories where Scandinavian burials or specific Scandinavian finds are known (Minasyan 1980, 68–74). Another characteristic feature of this group of knives is the use of an iron characterized by high hardness. The microhardness of the ferrite plates of the blade can reach 383–421 kg/mm^2; it is what is known as high-phosphorus iron.

   L.S. Rozanova and T.A. Pushkina were the first to notice the clear interdependence of the shape of the blade, the technology of its production, and the raw material used when studying smithing products from Gnezdovo in the Dnepr basin, Smolensk region. This archaeological site is similar to Shestovitsa because of its characteristics (Pushkina & Rozanova 1992, 200–219; Rozanova & Pushkina 2001, 77–82). It is worth pointing out that some knives with triple-welded blades come from burial mounds containing outstandingly rich sets of grave goods, including those of Scandinavian origin.

   The technological study of blacksmiths' products from southern Russian settlements of the 10th century lacking significant Slavic-Norman populations provides important evidence for this technology having been introduced to the craft skills of Russian blacksmiths from outside. Thus, the results of studying blacksmith's products from the Old Russian sites of the 10th–11th centuries in the forest-steppe region in the Bug River basin show that their technological characteristics are mostly limited to solid-metal and carbonized objects. Not one of the objects tested gave evidence of having been made by triple-welding (Voznesenskaya 2001, 122-127).

   The spread of triple-welded knives over the vast territories of eastern Europe was linked with international trade and so they naturally first appeared in the settlements of merchants and craftsmen that were its key bases. In this respect the observation made by M.F. Gurin is worth mentioning: the researcher has established that among triple-welded knives from the Polotsk land there are specimens that stand out from the whole corpus of finds by virtue of the trace elements in the steel plates. M.F. Gurin follows A. Antein, and believes that

the objects with high nickel contents in the steel could have been imported (or made of imported raw material), probably from Scandinavia (Gotland?) or central Europe (Gurin 1984, 311–326).

It should be noted out that the production of triple-welded knives clearly coincides chronologically with the operating of trading and craft centres: by the time of their decline, in the late 10th–early 11th centuries, the technologies of welding-in and welding-on steel blades had appeared in the blacksmith craft of Old Russia. The use of triple-welded blades gradually disappeared at the same time, and by the beginning of the 12th century they were rarely to be found among the other blacksmiths' output.

6. Knives with welded-on cutting edges (18 specimens). Thirteen of this group of knives were made using the traditional technique of frontal welding a steel cutting-edge on an iron core with subsequent heat treatment. Five other blades, however, were made by a technology that is extremely rare in the Old Russian blacksmiths' craft. Hard high-phosphorus iron plates were inserted between backs and steel cutting edges (see Fig. 64 and 65). The microhardness of ferrite in these plates was up to 383 kg/mm^2. The welded-on working edges were made of high-carbon steel, with martensitic microhardness ranging within 642-946 kg/mm^2.

   Most of the known specimens originate from small towns and settlements of the Chernigov region (Voznesenskaya 2005, 86-89). In addition to their similar technological process, they are united by one type of raw material, hard high-phosphorus iron. Like in case of pattern-welded knives, after polishing and special etching of the blade the high-phosphorus iron acquired a visual impact- a shiny bright stripe along the knife's blade, what was perceived as an ornament. Their shape assigns these knives to the type of narrow-bladed knives with straight and thick back (Minasyan's type IV). So far as chronology is concerned, some of the knives found in dwellings or refuse pits date from the 10th-11th centuries, while other come from cultural deposits of the 11th-12th and 10th-13th centuries. The knives from Shestovitsa may be considered to be the earliest ones, in view of their morphology, chronology, and the character of the site they originate from.

   The 10th-14th centuries knives with decorative strips of high-phosphorus iron (with straight or serrated welds between the strips and cutting edges) are known from archaeological sites of contemporary Czech Republic and Poland (e.g. Pleiner 1962, 154-155; Pleiner 1993; Hošek et al. 2009; Boháčová & Hošek 2009) and their sporadic occurrence in the Chernigov region indicates rather trade contacts than

diffusion (though limited) of the technique into Old Russian blacksmiths' craft.

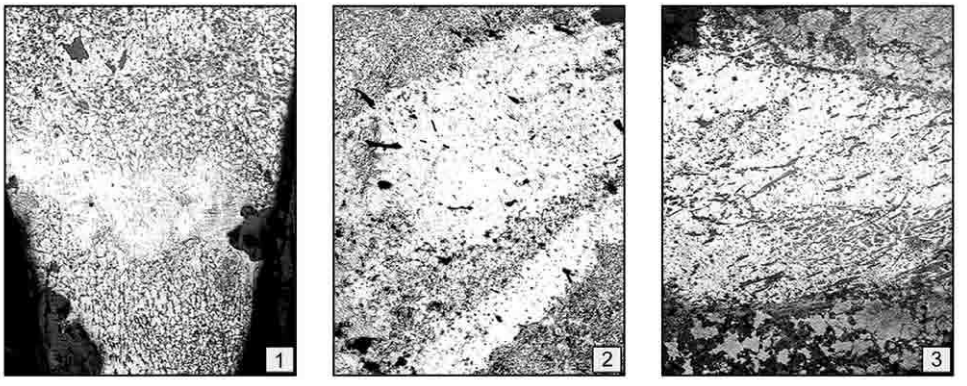

Figure 65: Microstructures of knives with inserted strips of high-phosphorus ferrite. 1, 3 – Shestovitsa (3270, 3457); 2 – Chernigov (3476). Photographs by G. Voznesenskaya.

On the basis of their technological characteristics the household knives from Shestovitsa can therefore be divided into two groups: knives made by the simplest technologies (solid-metal blades or those with carburized cutting-edges) knives made by constructive welding of iron and steel.

L.S. Rozanova and T.A. Pushkina have carried out a technical and technological investigation of the blacksmiths' products from the burial mound groups and settlements of Gnezdovo, and they single out two main production traditions in ironworking which might be termed Slavic and Scandinavian (Rozanova & Pushkina 2001, 79–80). Taking into consideration the substantial similarity of the technological characteristics of the Gnezdovo and Shestovitsa assemblages it seems reasonable to extrapolate this similarity in analytical data to the productive traditions developed in these settlements:

– *The Slavic production tradition* in the blacksmiths' craft of Shestovitsa is defined by solid-metal blades (both iron and steel) and the use of cementation when shaping artefacts.

– *The Scandinavian production tradition* is characterized by the active use of welding technology, and especially, especially triple welding. Metallographic tests on knives originating from the Late Iron Age cemeteries in Denmark (the Danish Vikings) have shown that, in addition to multilayer knives, all kinds of welded and welded-on blades were well known in northern Europe in the 6th–10th centuries (Lyngstrom 1995, 79–82).

Some centuries earlier the tribes of Jutland had also used the technological

schemes of three-fold welding, welding-in, and welding-on in their blacksmith craft, which is evident from the metallographic studies of knives from the well-known Illerup peat bog with sacrificial hoards dating from the Roman period (Youttijärvi 1994, 40–46). Thus, of the 195 knives from the settlement and burial mounds of Old Russian Shestovitsa 107 (about 55 %) were made in the Slavic productive tradition and 89 (about 45 %) in the Scandinavian tradition.

In conclusion it may be added that the rapid development of various crafts in medieval Europe owes a great deal to the heritage of the ancient world. As early as forty years ago R. Pleiner wrote that the craft of the blacksmith craft bloomed in the regions where the traditions of Roman provincial culture had earlier taken root, i.e. from Britain to the Danube area (Pleiner 1967, 112). The metalworking technologies invented by the craftsmen of the ancient world spread and developed in the Old Russian state thanks largely to the influence of the Scandinavian craft traditions.

References

Arrhenius, B. 1989, 'Arbeitsmesser aus den Gräbern von Birka', in G. Advisson, *Birka II: 3. Systematische Analysen der Gräberfunde* (Stockholm), 79-82.

Boháčová, I. & Hošek, J. 2009, 'Raně středověké nože ze Staré Boleslavi', *Archaeologia historica* 34, 367-392.

Gurin, M.F. 1984, 'Issledovanie trekhpolosnykh nozhei Polockoi zemli', *Slovenská archeologia XXXII/2*, 311-326.

Hošek et al. 2009: Hošek, J., Velímský, F., Šilhová, A. & Ottenwelter, E. 2009, 'Metallography of medieval knives from Malín (Bohemia)'; in *Archaeometallurgy in Europe 2007* (Milano : Associazione Italiana di Metallurgia), 272-281.

Jouttijärvi, A. 1994, 'Metalanalyser', in *Illerup Ådal. Proveniensbestemmelse af jern fra Illerup ädal - et pilotprojekt. Jysk Arkaeologisk Selskab* (Moesgård Museum), 40-46.

Kolchin, B.A. 1959, *Zhelezoobrabatyvayushchee remeslo Novgoroda Velikogo* (Moscow: Materialy i issledovaniya po arkheologii SSSR No. 65).

Kovalenko et al. 2003: Kovalenko, V., Mocya, A. & Sytyi, Yu. 2003, 'Arkheologicheskie issledovaniya shestovitskogo kompleksa v 1998-2002 gg.', in *Druzhinni starozhitnosti Centralno-Skhidnoe Evropi*

VIII-XI st. (Chernigov), 51-67.

Kovalenko, V.P. 2001, 'Novye issledovaniya v Shestovitse', in *Arkheologicheskii sbornik. Gnezdovo. 125 let issledovaniya pamyatnika* (Moscow: Trudy GIM Vol. 124), 190.

Lyngstrom, H. 1995, 'Knives from the Late Iron Age in Denmark', in I. Jansson (ed.), *Archaeology East and West of the Baltic* (Stockholm), 79-82.

Mazur, A. & Nosek, E. 1972, 'Wczesnośredniowieczne noże dziwerowane z Wrocławia', *Kwartalnik historii nauki i techniki* XVII (2), 291-306.

Minasyan, R.R. 1980, 'Chetyre gruppy nozhei Vostochnoi Evropy rannego srednevekovya (k Voprosu o poyavlenii slavyanskikh form v lesnoi zone)', in *Arkheologicheskii sbornik Gosudarstvennogo Ermitazha* 21 (Leningrad), 68-74.

Nosov, E.N. 1993, 'Problema proiskhozhdeniya pervykh gorodov Severnoi Rusi', in *Drevnosti Severo-Zapada* (Sankt-Peterburg), 59-77.

Nosov, E.N. 2002, 'Proiskhozhdenie Gorodov Severnoi Rusi (postanovka problemy: istoriya i arkheologiya)', in *Istoricheskie zapiski* 5 (123), (Moscow), 5-42.

Pleiner, R. 1962, *Staré evropské kovářství* (Praha: Academia).

Pleiner, R. 1983, 'Zur Technik von Messerklingen aus Haithabu', in *Berichte über die Ausgrabungen in Haithabu* 18 (Neumünster), 63-92.

Pleiner, R. 1993, 'Die Technologie der Messerherstellung in der Frühmittelalterlichen Fürstenburg von Budeč, Böhmen', *Památky Archeologické* 84, 69-92.

Pushkina, T.A. & Rozanova, L.R. 1992, 'Kuznechnye izdeliya iz Gnezdova', *Rossiiskaya arkheologiya* 2, 200-219.

Rozanova, L.R. & Pushkina, T.A. 2001, 'Proizvodstvennye tradicii v zhelezoobrabatyvayuschem remesle Gnezdova', in *Arkheologicheskii sbornik. Gnezdovo. 125 let issledovaniya pamyatnika* (Moscow: Trudy Gosudarstvennogo istoricheskogo muzeya Vol. 124), 77-82.

Rozanova, L.R. 1988, 'Tekhnologicheskie osobennosti v kuznechnom proizvodstve severo- i yuzhnorusskikh Gorodov', in *Istoriko-arkheologicheskii seminar "Chernigov i ego okruga v IX—XIII vv. Tezisy dokladov"* (Chernigov), 57-59.

Rozanova, L.R. 1989, 'Tekhnologiya kuznechnogo proizvodstva v gorodakh Novgorodskoi zemli. Novgorod i Novgorodskaya zemlya', in *Istoriya i arkheologiya* (Novgorod), 73-76.

Rozanova, L.R. 1991, 'Itogi metallograficheskogo issledovaniya kuznechnykh izdelii', in L.A. Golubeva & R.I. Kochkurkina 1991, *Belozerskaya Ves'* (Petrozavodsk), 166-181.

Rozanova, L.R. 1997, 'Puti razvitiya i formirovanie tradicii v kuznechnom remesle Drevnei Rusi', in N.N. Terekhova, L.R. Rozanova, V.I.

Zavyalov & M.M.Tolmacheva 1997, *Ocherki po istorii drevnei zhelezoobrabotki v Vostochnoi Evrope* (Moscow), 265-295.

Rozanova, L.S. 1994, 'K voprosu o tekhnicheskikh priemakh izgotovleniya zheleznykh izdelii iz Staroi Ladogi v doknyazheskii period', in *Novgorodskie arkheologicheskie chteniya* (Novgorod), 175-179.

Tolochko, P.P. 1989, *Drevnerusskii feodalnyi gorod* (Kiev).

Tomtlund, J.E. 1973, 'Metallographic Investigation of the 13 knives from Helgö', *Early Medieval Studies* 5, 42-63.

Voznesenska et al. 1996: Voznesenska, G.O., Nedopako, D.P. & Pankov R.P. 1996, *Chorna metalurgiya ta metaloobrobka naselennya skhidnoevropeiskogo lisostepu za dobi rannikh slovyan i Kievskoe Rusi* (Kiev).

Voznesenska, G.O. 2000, 'Tekhnika kovalskogo virobnictva v gorodku na Lováti', in *Arkheometriya ta okhorona istoriko-kulturnoe spadschini* 4 (Kiev), 18-28.

Voznesenskaya ,G.A. 1995, 'O slozhenii proizvodstvennykh traditsiyi v drevnerusskoi metalloobrabotke', *Arkheologiya* 3 (Kiev), 47-52.

Voznesenskaya, G.A. 1999, 'Tekhnologiya kuznechnogo proizvodstva na yuzhnorusskikh selskikh poseleniyakh', *Arkheologiya* 2 (Kiev), 117-126.

Voznesenskaya, G.A. & Kovalenko, V.P. 1985, 'O tekhnike kuznechnogo proizvodstva v gorodakh chernigovo-severskoi zemli', in *Zemli Yuzhnoi Rusi v XI—XIII vv.* (Kiev), 95-109.

Voznesenskaya, G.A. 2001, 'Tekhnologiya zhelezoobrabotki na drevnerusskikh gorodishchakh Yuzhnogo Buga', *Arkheologiya* 2 (Kiev), 122-127.

Voznesenskaya, G.A. 2005, 'Tekhnologicheskie osobennosti kuznechnoi produkcii drevnego Chernigova', *Arkheologiya* 4 (Kiev).

Voznesenskaya, G.A. 2005, 'Zhelezoobrabotka na poselenii v Shestovitse. Tekhnologicheskie tradicii', in E.N Chernykh, V.I. Zavyalov (eds.), *Arkheologiya i estestvenno-nauchnye metody* (Moscow), 101-113.

Voznesenskaya, G.A. 2006, 'Tekhnologicheskie osobennosti nozhei iz raskopok Shestovitskogo mogilnika', in *Rus na perekhresti svitiv. Mizhnarodni vplivi na formuvannya davnoruskoe derzhavi IX-XI st.* Chernigiv, 39-44.

Zavyalov, V.I. & Rozanova, L.R. 1990, 'K voprosu o proizvodstvennoi tekhnologii nozhei v drevnem Novgorode (po materialam Troickogo raskopa)', in *Kultura i istoriya srednevekovoi Rusi. Materialy po arkheologii Novgoroda. Tezisy konferencii* (Moscow), 154-172.

Further metallographic studies on early armour from Churburg

A. Williams

Thirteen elements from five suits of plate armour made in Milan during the late 14th and early 15th centuries and kept in Churburg Castle have been examined. Out of the late 14th/early 15th century examples, one has been successfully hardened by quenching and three more have had some increase in hardness brought about by attempts at heat-treatment. All of the mid-15th century examples have been hardened by quenching, four out of five to around 300-400 VPH.

Plate armour - Metallography - Churburg - South Tirol - Italy

Introduction

The suit of plate armour was a unique European invention, which does not resemble body armour made in any other culture. It was first developed in North Italy during the course of the 14th century, and reached a level of excellence by the middle of the 15th century. Lombardy, and especially Milan and Brescia, had developed a considerable industry in the manufacture of arms and armour before 1300, but the production of the large plates needed for an articulated suit of plate placed new demands upon the metallurgy of the time.

Large quantities of armour from the 16th century and later survive, but complete suits of armour from the 15th century are scarcer. One of the most important collections of complete early armours is the collection of the Counts Trapp in their castle of Churburg, now in North Italy. The author was allowed to study a large number of these important armours by microscopic examination (Williams 1986). Subsequently, further armours at Churburg have been examined, and the results are published here.

Methods of investigation

Surface hardness measurements were taken with a Branson-Krautkramer electronic hardness tester. Metallography was carried out in the Wallace

Collection Conservation Department. Some electron microanalysis was carried out in the Department of Materials Science and Metallurgy, Cambridge University.

Churburg 18 (*c* 1370–1410)

This is a composite armour (see Fig. 66 /Plate XX/), made up of a one-piece breastplate (with a lower plate attached) a two-piece backplate, lower arm- and leg-defences, and an armet (a helmet made of three plates hinged together) with its visor missing. This helmet has the master-mark **T** (twice on the tail-piece, and once on either cheekpiece). The vambraces bear the master-mark of a gothic **O**. Scalini dates the helmet to *c* 1370 and the body armour to 1370–1410. It is not known whether the gauntlets belonged.

Figure 66: Armour (Churburg 18). Photograph by courtesy of Count Trapp.

It is exhibited with spaulders, to protect the shoulders, which may be later, according to Scalini (*op.cit.* 69). The discs at the front of the

spaulders have the master-marks **S** and **BG** as well as punched decoration in the form of bears. Master T and Master O seem to be unidentified; the other marks might be Master Biagio for Giovanni Spanzotti. Weights; Breastplate 3.6kg, backplate 3.7kg, armet 3.62kg.

Surface hardness readings: the backplate varied from 176 to 256 VPH. The plate below the breastplate (fauld) averaged 274 VPH. The armet ranged from 280 (skull) to right cheekpiece 335, left cheekpiece 540 VPH.

I. A sample was detached from inside the left cheekpiece of the armet (visored helmet). The microstructure appears to consists of ferrite and slag only. There is considerable variation in the size of the ferrite grains (Fig. 67: a). Microhardness (Vickers, 100g) range = 174–230; average = 201 VPH.

Another sample was detached from a delamination at the tail of the skull. The microstructure consists of ferrite and small areas of irresolvable carbides (perhaps 0.1%C). Its hardness is unexpectedly high. This may have been a low-carbon steel that has been given an attempted hardening (Fig. 67: b).

II. A sample was detached from inside the breastplate. The microstructure appears to consist of ferrite and slag only. However, the surface hardness of the breastplate ranges from 280 to 345 VPH, so this seems to have been a steel of varying carbon content that has been given an attempted hardening.

III. A sample was detached from the rim of the right gauntlet. The microstructure consists of tempered martensite, some of which is acicular in appearance (so it might in fact be bainite) mixed with grains of ferrite, arranged in bands along the surface, but without visible pearlite (Fig. 68: a). This is a medium-carbon steel which has been hardened by quenching. Microhardness (Vickers, 100g) range = 305-429; average = 365 VPH.

IV. A sample was detached from delaminations inside the top fauld plate (plate below the breast) (1), inside the backplate (2), and inside the plate below the backplate (3).

1. The microstructure consists of ferrite and small areas of granular carbides (perhaps 0.1% C). This seems to have been a low-carbon steel that has been given an attempted hardening.

2. The microstructure consists of pearlite and ferrite (perhaps 0.6%C) with very little slag. This is a medium-carbon steel which has not been hardened by quenching (Fig. 68: b). Surface hardness readings: average = 256 VPH.

3. The microstructure consists of ferrite and slag only.

V. A sample was detached from a delamination inside the 3rd lame from the bottom of the left spaulder (shoulder defence). The microstruc-

ture consists of very small-grained ferrite and slag inclusions. But the average surface hardness readings were 210 and 216 VPH, again suggesting a quenched low-carbon material.

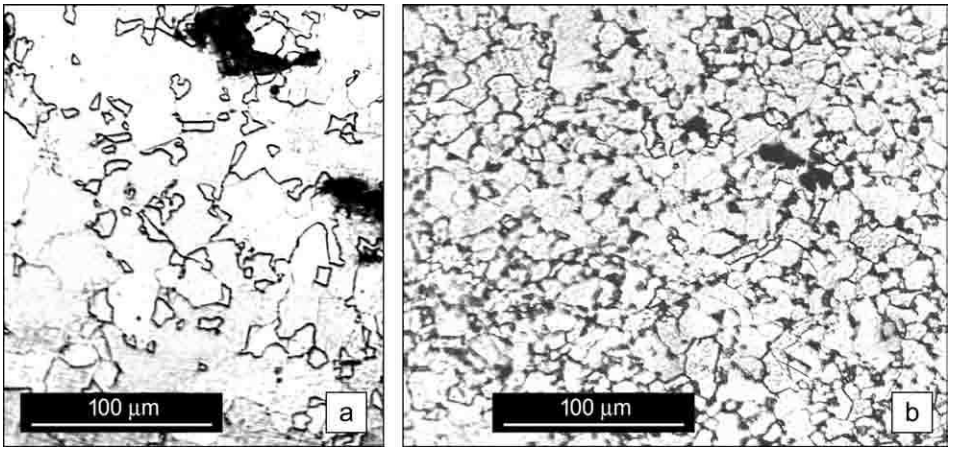

Figure 67: Armour (Churburg 18): a – microstructure of sample from cheekpiece of the armet; b - microstructure of sample from the tail of the skull. Photomicrograph by A. Williams.

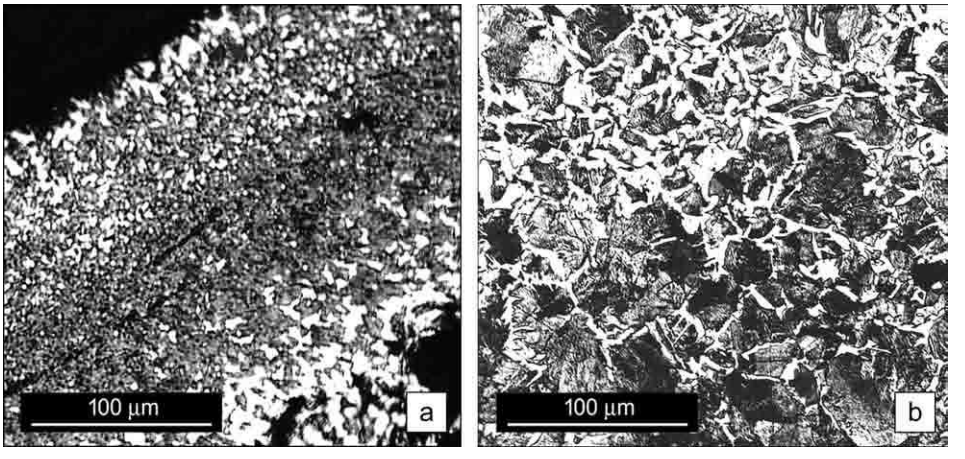

Figure 68: Armour (Churburg 18): a – microstructure of sample from the right gauntlet; b - microstructure of sample from the backplate. Photomicrographs by A. Williams.

Out of the five elements from this armour, one has been definitely quenched to harden it, another three possibly quenched, and one definitely not. It may well be that this early armour was produced before any regular control of the raw material had been established, and so hardening was carried out, but with rather unpredictable results.

A sample from a Milanese helmet (Churburg 13) of c 1365 examined earlier by the author also had a ferritic microstructure of unusual hardness

(180 VPH), suggesting another quenched low-carbon material (Williams, 2003, 69). Re-examination in an SEM found neither phosphorus nor manganese in the metal matrix: Si 0.18, Ca 0.06, Mn 0, Al 0.39, K 0, S n.d, P 0, Mg n.d (atomic %).

Churburg 16

A bascinet, made up of a one-piece skull and visor. *c* 1385, see Fig. 69.

The bascinet skull has the stamp **ARCO** (perhaps an ownership mark of a Count d'Arco) and the master-mark of a star. Total weight 4.09 kg. Surface hardness readings: bascinet skull average = 234 VPH.

Figure 69: Bascinet (Churburg 16). Photograph by courtesy of Count Trapp.

A sample was detached from a delamination inside the skull, near the crown. The microstructure consists of very small-grained ferrite and areas of pearlite as well as slag inclusions (perhaps 0.2% C), see Fig. 70: a. Average microhardness = 202 VPH.

Subsequent examination in an SEM found neither phosphorus nor manganese in the metal matrix of the skull: Si 0.25, Ca 0, Mn 0.28, Al 0.47, K 0, S n.d, P 0, Mg 0.18 (atomic %).

The visor, however, has the master-mark of a six-petalled flower, so it may not belong to the skull, although they are of similar size and date. Surface hardness readings: bascinet visor average = 223 VPH.

A sample was detached from inside the visor near the right hinge. The microstructure consists of ferrite and areas of pearlite (perhaps 0.2% C), see Fig 70: b.

The associated breastplate (Churburg 14), Fig. 71: a, has the master-

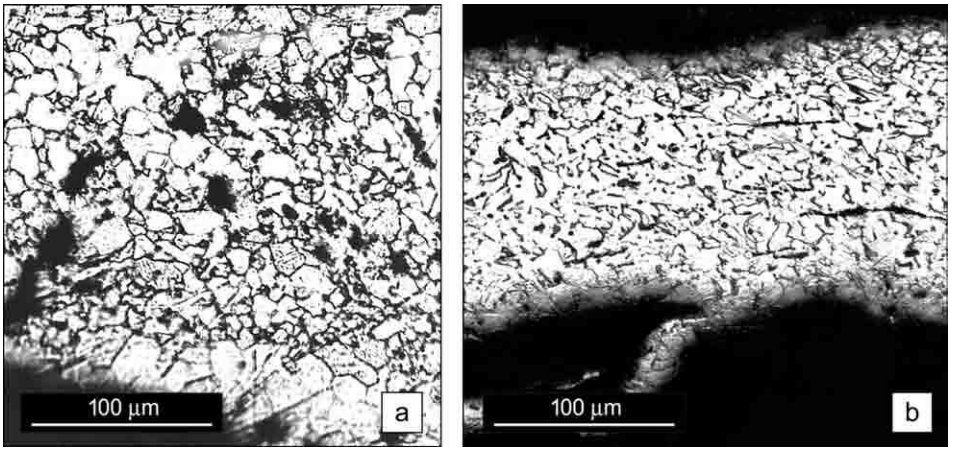

Figure 70: Bascinet (Churburg 16): a - microstructure of sample from skull; b - microstructure of sample from visor. Photomicrographs by A. Williams.

marks of **P** (Scalini, *op.cit.*, 44) dates it to c 1385) who may have been Petraiulo de Missaglia (weight 2.6 kg).

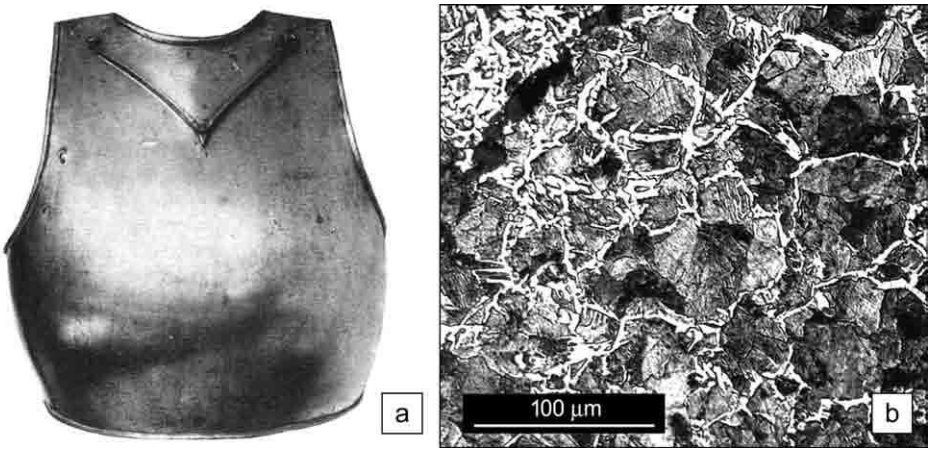

Figure 71: Breastplate (Churburg 14): a – the breastplate; b - microstructure of the examined sample. Photograph by courtesy of Count Trapp. Photomicrograph by A. Williams.

Surface hardness readings: breastplate average = 269 VPH. A sample was detached from a delamination inside the breastplate. The microstructure consists of pearlite and ferrite (perhaps 0.6% C), see Fig. 71: b. This is a medium-carbon steel which has not been hardened by quenching. Microhardness (Vickers, 100g) = 241 VPH.

Churburg 21

The armour of Galeazzo d'Arco (see Fig. 72 /Plate XXI/) bears workshop marks of a crowned **my** and an **m** below a split cross in several places, including the helmet. The marks are probably those of the workshop of Tommaso Missaglia. Scalini dates this armour to 1445–50. This armour is now exhibited with the armet (visored helmet) catalogued as Churburg 20.

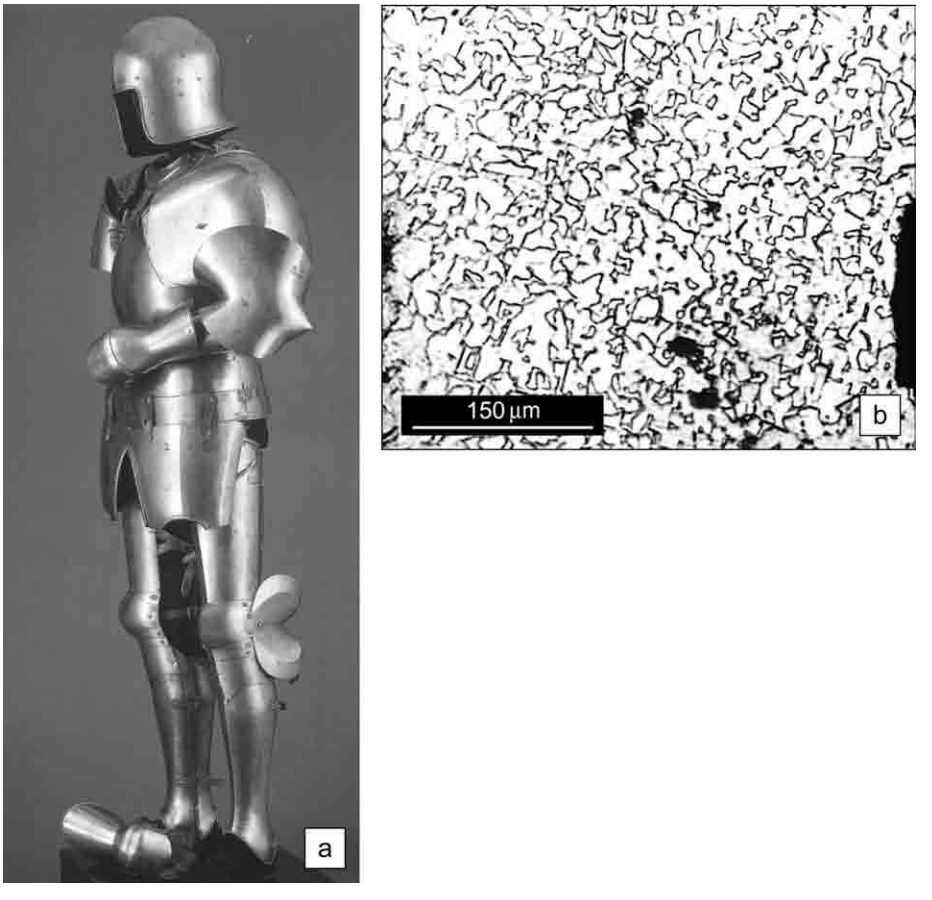

Figure 72: Armour Churburg 21 exhibited with a sallet (open helmet): a – the armour; b - microstructure of sample from left pauldron. Photograph by courtesy of Count Trapp. Photomicrograph by A. Williams.

Surface hardness readings: breastplate ranged from 125 to 340 VPH; backplate, average = 336 VPH; left pauldron ranged from 182 to 355 VPH; left vambrace average = 306 VPH.

I. A sample was detached from the side of the main plate of the left pauldron. The microstructure consists of ferrite and carbides only: this seems to be a quenched low-carbon steel, see Fig. 72: b. Microhardness

(Vickers, 100g) range = 228–274; average = 244 VPH.

II. A sample was detached from the wrist end of the left lower vambrace. The microstructure consists of a fairly uniform mix of areas of martensite, somewhat tempered, surrounded by pro eutectoid ferrite (sometimes in a spiny form) and a little pearlite (Fig. 73: a, b). There are very few slag inclusions. This is a medium-carbon steel which has been hardened by quenching. Microhardness (Vickers, 100g) range = 315-393; Average = 355 VPH.

III. A sample was detached from the lower edge of the backplate. The microstructure consists of a network of grains of ferrite, largely equiaxed, mixed with areas of martensite, and an acicular material which may be bainite, but no pearlite (Fig. 73: c). It was not possible to measure the microhardness.

IV. Sallet (formerly exhibited on Churburg 21). Weight = 2.87kg; surface hardness readings range from 228 to 490, average = 315 VPH. A metallographic examination of this helmet has already been published (Williams, 1986). The microstructure consisted of martensite, nodular pearlite and ferrite with a few slag inclusions (Fig. 73: a). The microhardness (average) = 344 VPH. This is a medium-carbon (around 0.5%C) steel which has been hardened by some form of heat-treatment, probably a slack-quench.

Churburg 59

Barbuta (or 'Venetian' sallet) with the master-mark **PR** (perhaps that of Provasio di Milano), *c* 1470, Fig. 74: a.

A sample was detached from inside the barbuta. The microstructure consists of areas of martensite, somewhat tempered, containing equiaxed grains of ferrite (apparently a lower-carbon area) but no pearlite, see Fig. 74: b. There are very few slag inclusions. The microhardness ranges from 193 to 397 VPH. This is a steel, of variable carbon content, which has been hardened by quenching.

Discussion and conclusion

The earlier (14th century) components of armour often show some evidence of heat-treatment, although the carbon content was not always high enough for the steel to be significantly hardenable. These early examples (CH 18, 16 and 14) may be contrasted with later armours such as the AVANT armour (formerly at Churburg, CH20; and now in the Glasgow

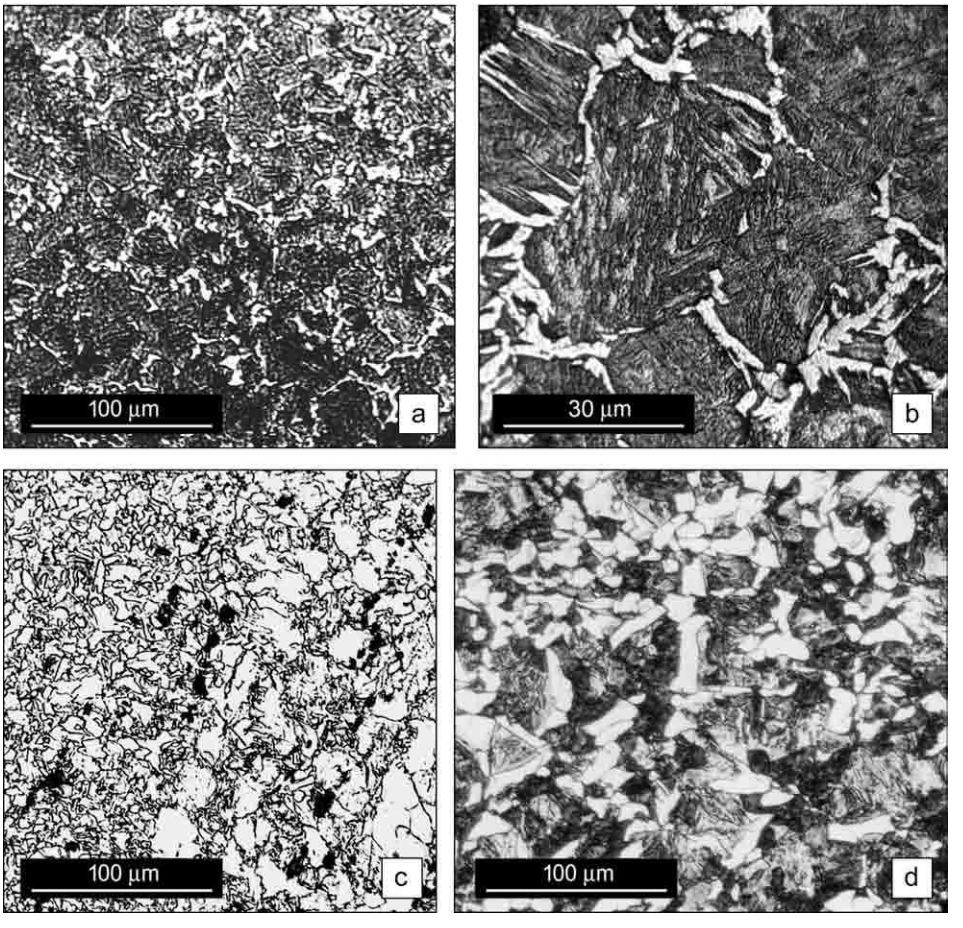

Figure 73: Armour (Churburg 21): a – microstructure of sample from left lower vambrace (arm-defence); b - microstructure of sample from left lower vambrace (detail); c - microstructure of sample from backplate; d - microstructure of sample from sallet. Photomicrographs by A. Williams.

Museum and Art Gallery, Kelvingrove; so-called because of an engraved motto), CH 21 and CH59. The AVANT armour was probably made in the workshop of the Corio brothers around 1440. Nine of its components were examined in cross-section, and all but one of them were medium-carbon steels which had been hardened by some form of heat treatment. These eight microstructures contained a mixture of martensite, pearlite, and ferrite, and were apparently the products of slack-quenching, to give hardnesses in the range 300–400 VPH. The ninth was made of a low-carbon steel which had also been quenched in an attempt to harden it (Williams 1986).

By the 15th century the steels available in Milan seem to have been much more consistent in their carbon contents, and the hardening of ar-

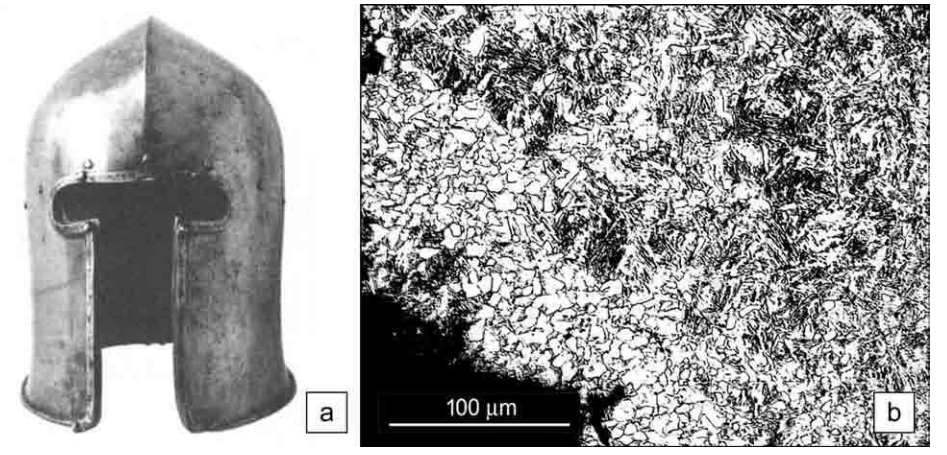

Figure 74: Barbuta (Churburg 59): a – the barbuta; b - microstructure of the examined sample. Photograph by courtesy of Count Trapp. Photomicrograph by A. Williams.

mour (as shown by CH 20, discussed earlier; and 21 and 59, discussed here) was accordingly more successful.

Acknowledgements

The author would like to thank Count Johannes Trapp for his interest, his permission to undertake analysis, and also to publish these photographs of his armour, and also Keren Butler, for operating the electron microscope, and Professor Radomír Pleiner for his encouragement over many years past.

References

Scalini, M. 1996, *The Armoury of the Castle of Churburg* (Udine).

Trapp, O. 1929, *The Armoury of the Castle of Churburg*. Trans. J.G. Mann. London 1929, (reprinted 1996, Udine).

Williams, A. 1986, 'Fifteenth century armour from Churburg; a metallurgical study', *Armi Antiche* 32, 3-82.

Williams, A. 2003, *The Knight and the Blast Furnace* (Leiden–Boston).

From Soissons to Beauvais: the use of iron in some French cathedral

P. Dillmann

Samples were taken on ferrous reinforcements of three French cathedrals (Beauvais, Amiens, and Soissons) located in Picardy. They were analysed using classical metallographic methods and slag inclusions analytical methodology already set up to distinguish ironmaking processes and homogeneous groups. The results made it possible to place the ferrous reinforcements in their historical and technological contexts, which differ for each monument.

Bloomery process - Indirect process - Iron - Cathedrals

Introduction

Over the last ten years in France multidisciplinary studies that have brought together archaeologists, historians, and chemists have made it possible to demonstrate that significant weights of iron reinforcements were used in building medieval monuments. This is, for example, the case for the Palais des Papes in Avignon (Dillmann *et al.* 2003; Bernardi & Dillmann 2005; Dillmann *et al.* 2004), Rouen cathedral (Dillmann & L'Héritier 2007; Barret *et al.* 2006; L'Héritier *et al.* 2005; Dillmann *et al.* 2004), or Vincennes Castle (Amoudruz *et al.* 1997; Clément-Charpentier 2001). These studies have revised opinions on the use of ferrous materials in the architecture of this period.

The present paper will focus on three monuments of French Gothic architecture, all located in Picardy: the cathedrals of Beauvais, Soissons, and Amiens. The aim will be here to show different applications of slag-inclusion analyses using the NRC ratio approach (Dillmann & L'Héritier 2007). This makes it possible on the one hand to determine the ironmaking process used to obtain the iron, and on the other to verify the homogeneity of some of the samples. Depending on the case, this information will help to date the ferrous reinforcement or to better understand the way they were put in the building.

Methodological aspects

All samples have been studied following the classical metallographic approach detailed elsewhere (Dillmann & L'Héritier 2007). Samples were polished in a water medium using SiC paper grade 80 to 1200 and finished with Struers diamond paste (3 and 1μm) (Pokorny & Pokorny 1994).

Carbon contents and distribution were studied by optical metallographic using nital 4% etching. Phosphorus distribution was evaluated using Oberhoffer etching after repolishing the samples (Vega *et al.* 2002).

Slag inclusion composition analyses were performed after repolishing using an Energy Dispersive Spectrometry (EDS) system (IDEFIX setup, SAMx company) coupled with a SEM (Cambridge Stereoscan 120). The IDEFIX system comprises a hardware setting, including a Si(Li) detector with a beryllium thin window and a numerical acquisition chain, and a software package for acquisition and processing of the x-ray spectra. Measurements were performed at 15kV accelerating voltage. A relative error of 2% is estimated for measurements of major elements, and 10% for minor elements with concentrations down to 0.5wt-% (detection limit). Moreover, for slag inclusion analysis, inclusions resulting from additions during forging and unrepresentative of the smelting stage were eliminated following the procedure proposed by Dillmann and others (Dillmann *et al.* 2004; Dillmann & L'Héritier 2007). Applying this procedure to each artefact allows an average weighted content to be expressed for slag inclusions. This content takes into account the surface of each inclusion resulting from the smelting stage. It is calculated as follows:

$$\%E^* = \sum_{i=1}^{N} \left(\%E_i \times \frac{S_i}{S_T} \right)$$

$\%E^*$: average weighted content for a given element or oxide
$\%E_i$: mass content of the element or oxide in the i slag inclusion
S_i : surface of the i slag inclusion
S_T : total surface of all the analysed inclusions
N : total number of inclusions

It can be assimilated to a pseudo macroscopic average content and thus be compared with the macroscopic slag composition. In what follows this average weighted content will be noted with a * symbol, following the element (or oxide) name. Moreover, slag-inclusion weighted average contents were reported in the abacus proposed by Dillmann and others (e.g. Dillmann & L'Héritier 2007) to distinguish the bloomery from the indirect processes.

Samples

In the south arm of the transept of the Saint-Gervais-Saint-Protais Soissons Cathedral, the gallery is reinforced by seven tie-rods going through the vault (see Table 9). An adjoining chapel was also reinforced in the same way using three tie-rods (see Fig. 75 /Plate XXII/). The transept building date is 1176, and so the use of ferrous reinforcements at this period can be questioned. These reinforcements could have been put in the building during the 19th century as claimed by Viollet-Le-Duc. Actually this author indicates an important explosion of a powder magazine near the cathedral in 1813 and supposed that the tie-rods were put at this place during the rebuilding of a part of the transept (Viollet-Le-Duc 1854, 195). The specimens taken total several cubic millimetres. This restricted size is needed because the reinforcement is still in use. To avoid representativity problems, a sample was therefore taken at each extremity of the tie-rod. A specimen was also taken on tie-rod 4 fastener: T4SE.

Table 9: Samples from Soissons and Beauvais Cathedrals.

Cathedral	Sample	Dating	Type	Location	Remark
Soissons	T1I, T1E, T2I, T2E, T4I, T4E, T3I, T3E, T5I, T6E, T6I, T7I, T7E, T4SE	?	Tie-rod	South transept, Gallery	South transept building date 1176 in the sample name
Soissons	TN, TS, TSE, TSI	?	Tie-rod	Chapel near the gallery of the south transept	
Beauvais	C2NC3NBI, C2NC3NCT, CN1BECN2, C2NC1NAI, C2NC3NAI, CN1CN2AC, C2NEC1	?	Tie-rod	Between the flying buttresses in the northern part of the choir	Replaced in 20th century; 18 century graffiti
Beauvais	C01, C02	?	Massive hook	Lateral walls of the attic	
Beauvais	M01, M02, M03, M04, M07	?	Link of a chain	Through the attic	

A great deal of ferrous reinforcements have been found in the structure of Beauvais Cathedral, the most spectacular being the massive tie-rods between the flying buttresses. Most of them were replaced during a restoration campaign at the end of the 20th century. However, during these works the former elements were kept and samples taken for analyses. One of the reinforcing tie-rod located in the flying buttresses in the south part of the choir show a graffiti indicating the year 1714. Other graffiti were found

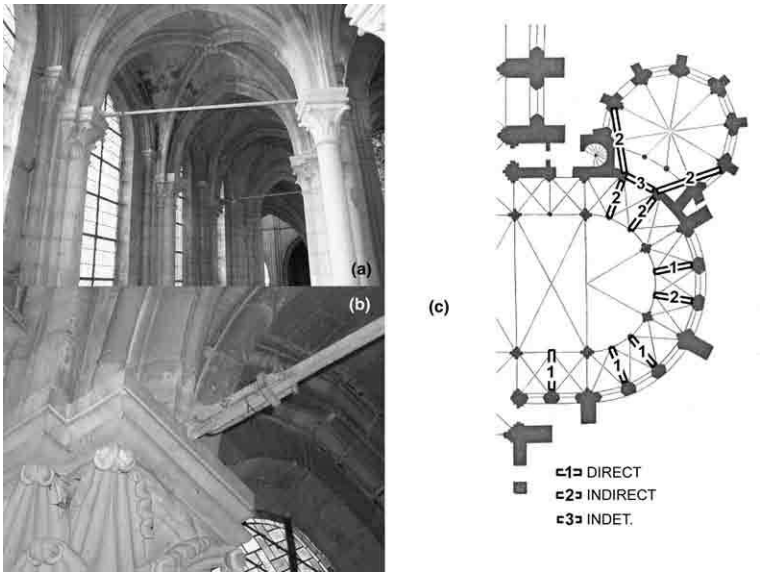

Figure 75: Soissons Cathedral. South transept (a) ferrous reinforcement in the gallery; (b) close-up view of a fastener; (c) ferrous tie-rod location and process, 1: bloomery process, 2: indirect, 3: undetermined. Original plan: Viollet-Le-Duc.

on several other flying buttresses, engraved in the stone and dated from the 18th century, indicating restoration work in this period. It is for these reasons that the tie-rods between the flying buttresses were all assumed to have been added during this century (see Fig. 76 /Plate XXII/). The surfaces of all the selected samples covered several tens of square centimetres and may be considered to be representative of the entire tie-rod. There was another sampling campaign in the attic, where two hooks are sealed into the side walls. There is also a chain that goes through the choir in the attic and several samples were taken on the accessible links. These samples are of several cubic millimetres; several samples were taken on each link in order to ensure a good representativity (Table 9).

In Amiens Cathedral, two chains that maintain the structure were found at different places. The best known goes all round the triforium. Several historical sources described the circumstances that led to the insertion of this reinforcing chain at the end of the 15th century (Lefebvre 2006), in order to prevent the central pillars collapsing. The historical archives indicate that the expert commission responsible for ordering the chain advised that only *fer d'Espagne* should be used to make it. At that time this term was associated with materials obtained by the bloomery process and coming from the general area of southern France or the Iberian Peninsula. This term could have been used to distinguish this material from those produced using the indirect process in an area (French Picardy) where the

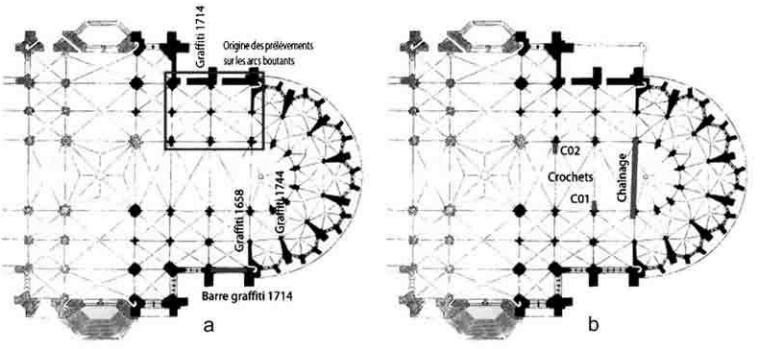

Figure 76: Sample locations in Beauvais Cathedral. (a) between the flying buttresses; (b) in the attic. Original plan: Viollet-Le-Duc.

latter process was in general use. 54 samples were taken on 35 of the 84 links of the chain (see Table 10). The chain, which is in fact made up of eight separate parts, consists mainly of 'standard' links of the same shape and dimensions. In some parts of the chain, however, this 'standardization' is not respected. At the ends of the chain in particular some of the links are smaller in length and cross-section, form, and surfaces and seem to have been forged in a different way (different surface aspect). Some of these extremities take the form of a crow's foot with three branches. Each end is fixed in a pillar or a wall by means of vertical anchors. The sample sizes are several tens of cubic millimetres in size. In order to avoid any problems of representativity, several different samples were taken on each link analysed.

The second chain, discovered more recently during the archaeological survey by Emeline Lefebvre, is located in the upper gutter of the southern side of the southern arm of the transept. The links of this chain are smaller than those of that of the triforium. Eleven specimens were taken on the links and on the anchors at the end of the chain. Four complementary clamps were taken on the triforium soil and in the south transept western side.

Results

Soissons Cathedral

Slag inclusion analysis results are presented in Table 11. They are also plotted in the abacus developed by Dillmann *et al.* to distinguish the processes (Fig. 77). On the basis of these data, the samples can be classified in different groups:

Table 10: Samples from Amiens Cathedral.

Name	Localisation	Remarks	Morphological specificity
IVW, VIE, VIW, VIIIW, VIIIE, XW, XE, XIIW, XIIE, XIVE, XIVW	Triforium chain Nave north	'Standard'	
XVIN	Triforium chain North transept, west side	Chain end going through a pillar	Chamfrain
XVIIIN, XVIIIS, XXN, XXS	Triforium chain North transept, west side	'Standard'	
XXIV	Triforium chain North transept, east side	'Standard' link	
XXVIIIP	Triforium chain North transept, east side		Shorter than standard ones
XXXN, XXXIS	Triforium chain North transept, east side	'Standard' link	
XXXIIIE	Triforium chain Choir northern side	Chain end going through a pillar	
XXXIVP, XXXIVW, XXXIVE, XLIIP, XLIIW	Triforium chain Choir northern side	'Standard' link	
XLVIE	Triforium chain Choir northern side	Smaller link	Chamfrain
XLVIIEc	Triforium chain Choir northern side	Crow's feet branch	Crow's feet
XLVIIb	Triforium chain Choir northern side	Crow's feet branch	Crow's feet
XLVIIBV	Triforium chain Choir northern side	Vertical tie-rod fastening the chain at one end	
XLIXS	Triforium chain Choir southern side	Perpendicular tie-rod with crow's feet fastening	
LBV	Triforium chain Choir southern side	Vertical tie-rod fastening the chain at one end	
LW, LIIP, LIIW, LIVPatte, LIVE, LVIP, LVIE	Triforium chain Choir southern side	'Standard' links	
LVIIIE	Triforium chain Choir southern side	Chain end, bar going through a pillar	
LXP, LXS, LXII S, LXIIN	Triforium chain South transept eastern side	'Standard' links	
LXIIIS, LXVIS	Triforium chain South transept eastern side	'Standard' links	Chamfrain
LXVIIS, LXIXN, LXXIN, LXXIVNb	Triforium chain South transept eastern side	'Standard' links	
LXXVS	Triforium chain South transept western side	Chain end, bar going through a pillar	
LXXVIW	Triforium chain Nave, southern side	Chain end, bar going through a pillar	
LXXVIIW, LXXXIE, LXXXIVW, LXXXVIIW	Triforium chain Nave, southern side	'Standard' links	
Anchor A	Nave, northern side	anchor	
Anchor T	Nave, southern side	anchor	
Agr 74	Soil of the triforium	clamp	
Agr 3T	Soil of the triforium	clamp	
Agr MD2-8	South transept western side	clamp	
Agr MD2-7	South transept western side	clamp	
TS01, TS02, TS03	Chain of the southern arm of the transept Upper gutter	links	
TS05, TS06	Chain of the southern arm of the transept Upper gutter	Vertical rod, Anchor, west side	
TS08	Chain of the southern arm of the transept Upper gutter	Rod in the stair tower	
TS09	Chain of the southern arm of the transept Upper gutter	Rod in the stair tower (idem TS09)	
TS10	Chain of the southern arm of the transept Upper gutter	Vertical rod, Anchor, east side	

– Specimens linked to the bloomery process and characterized by a low phosphorus content ($_{\text{mass}}\%P2O5^{*} < 5$): T3I, T3E, T5I, T6E, T6I, T7I, and T7E

Table 11: Average weighted composition ($_{mass}$%) (Dillmann & L'Héritier, 2007) of slag inclusion from the samples taken on the Soissons Cathedral.

Name	MgO^*	$Al_2O_3^*$	SiO_2^*	$P_2O_5^*$	SO_3^*	K_2O^*	CaO^*	TiO_2^*	$V_2O_5^*$	$Cr_2O_3^*$	MnO^*	FeO^*
T1 E	< 0.25	0.56	11.23	6.41	1.62	< 0.25	1.02	< 0.25	< 0.25	< 0.25	< 0.25	65.81
T1 I	< 0.25	0.50	11.77	8.37	3.71	< 0.25	2.57	0.59	1.31	0.83	< 0.25	73.56
T2 E	< 0.25	< 0.25	8.71	18.26	1.81	< 0.25	2.54	< 0.25	0.31	< 0.25	< 0.25	68.22
T2 I	0.39	< 0.25	5.19	9.77	1.03	< 0.25	0.70	< 0.25	0.31	< 0.25	< 0.25	81.88
T3 E	< 0.25	7.78	28.40	0.81	0.57	1.67	3.22	< 0.25	< 0.25	< 0.25	0.46	55.99
T3 I	0.27	8.41	28.11	2.18	0.77	1.62	2.82	0.26	< 0.25	< 0.25	0.55	54.54
T4 E	< 0.25	0.65	4.76	13.80	2.69	< 0.25	0.51	< 0.25	< 0.25	< 0.25	0.59	60.60
T4 I	< 0.25	0.72	2.99	24.30	4.07	1.12	4.87	< 0.25	< 0.25	< 0.25	0.16	39.25
T5 I	3.23	17.52	65.35	1.06	0.87	2.12	2.81	0.47	< 0.25	< 0.25	0.62	76.13
T6 I	0.26	4.92	21.46	1.18	0.60	1.35	3.00	< 0.25	< 0.25	< 0.25	0.27	80.10
T6 E	1.27	9.57	41.99	2.15	1.07	1.70	3.73	0.30	< 0.25	< 0.25	0.55	4.34
T7 I	< 0.25	7.52	33.71	1.42	0.80	1.40	2.17	< 0.25	< 0.25	< 0.25	0.66	80.38
T7 E	0.68	9.30	40.04	2.75	1.66	1.63	2.52	< 0.25	< 0.25	< 0.25	1.19	36.62
TS E	< 0.25	< 0.25	6.49	9.13	1.63	< 0.25	0.60	< 0.25	0.34	< 0.25	0.21	53.05
TS I	0.28	< 0.25	6.20	9.70	1.36	< 0.25	0.58	< 0.25	0.49	< 0.25	0.24	86.67
TN	0.74	0.38	2.39	6.62	0.92	< 0.25	0.59	< 0.25	0.48	0.34	0.12	51.53
T4SE	< 0.25	1.30	19.54	0.42	0.58	0.31	0.59	< 0.25	< 0.25	< 0.25	23.28	66.29

- Specimens linked to the indirect process with a high phosphorus level: T1I, T1E, T2I, T2E, T4I, T4E, TSE, TSI, TN
- The T4SE specimen with a high MnO^* content in the slag inclusions and an indeterminate ironmaking process.

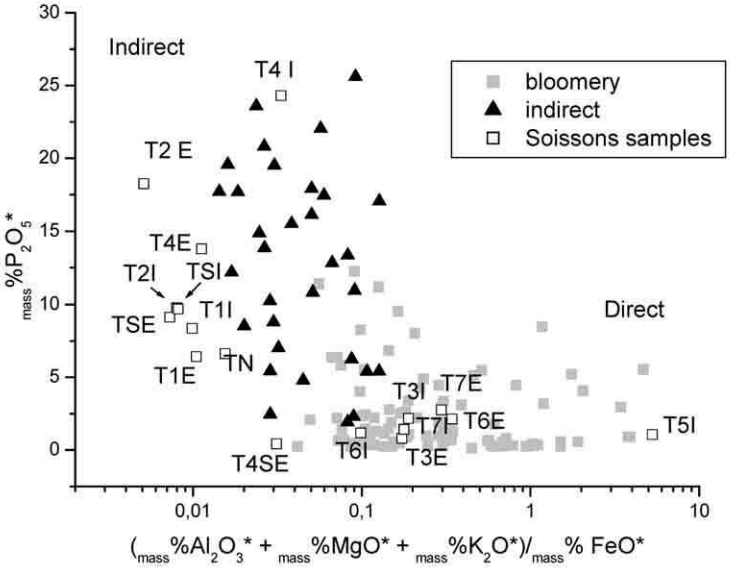

Figure 77: Smelting process identification by slag inclusion analysis (Dillmann & L'Héritier, 2007). Specimens taken on Soissons Cathedral.

Tie-rods T1, T2, T4, TS, and TN seem to result from the indirect process. Moreover, they have low-carburized microstructures, most of which

are completely ferritic (Fig. 78 and Table 12 /Plate XXIII/). The slag-inclusion cleanliness is very low. At the other hand, tie-rods T3, T5, T6, and T7 seem to have been made using the bloomery process. Their metallographic structures are generally more heterogeneous than those of samples associated with the indirect process and the carbon contents are also higher, approaching $0.4_{\text{mass}}\%$ (Fig. 79 and Table 12 /Plate XXIII/). As for the indirect process samples, inclusion cleanliness are very low.

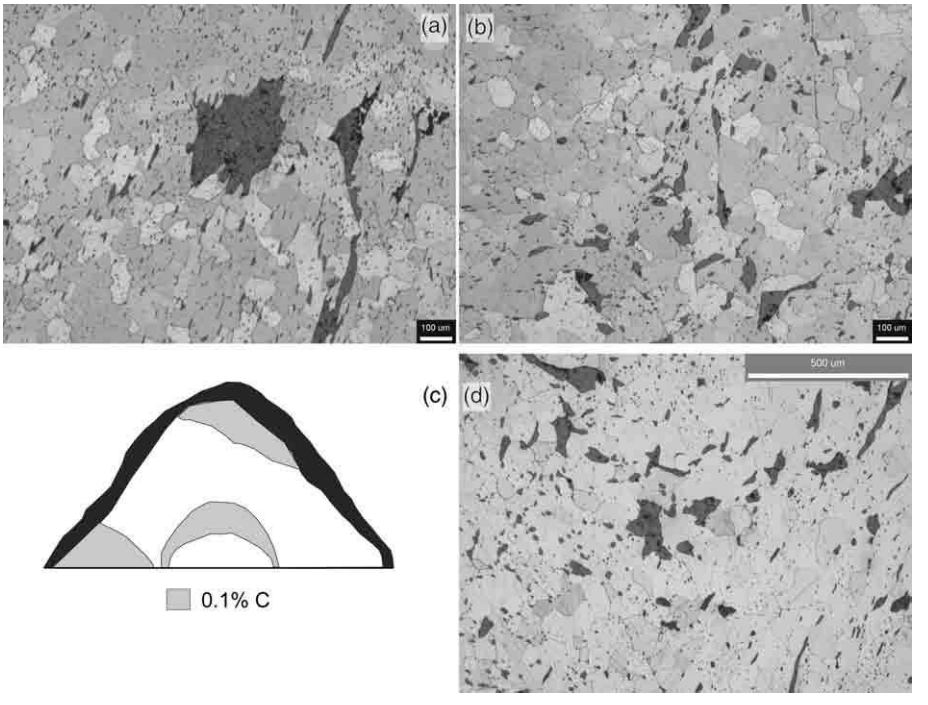

Figure 78: Microphotographs obtained on samples (a) T1E, (b) T2I, (c) T4 I – schematic of the structure and (d) TN after nital etching.

These results show that at least some of the tie-rods of the southern arm of the transept of Soissons Cathedral were not installed during its construction because they were made using the indirect process, which was not in use in this area during the 12th century. Some of the tie-rods in the cathedral were in fact obtained by the bloomery process and could have been put in the southern transept during the building of this part of the cathedral, or at least during the period when the bloomery process was dominant in Europe (i.e. before the 14th century for French Picardy). A third hypothesis could be these tie-rods were imported from areas in other part of Europe (as the south of France or Spain) where the bloomery process was still in use.

In the same way, the use at the same time of tie-rods coming from different processes and that have the same function is unlikely and cannot be

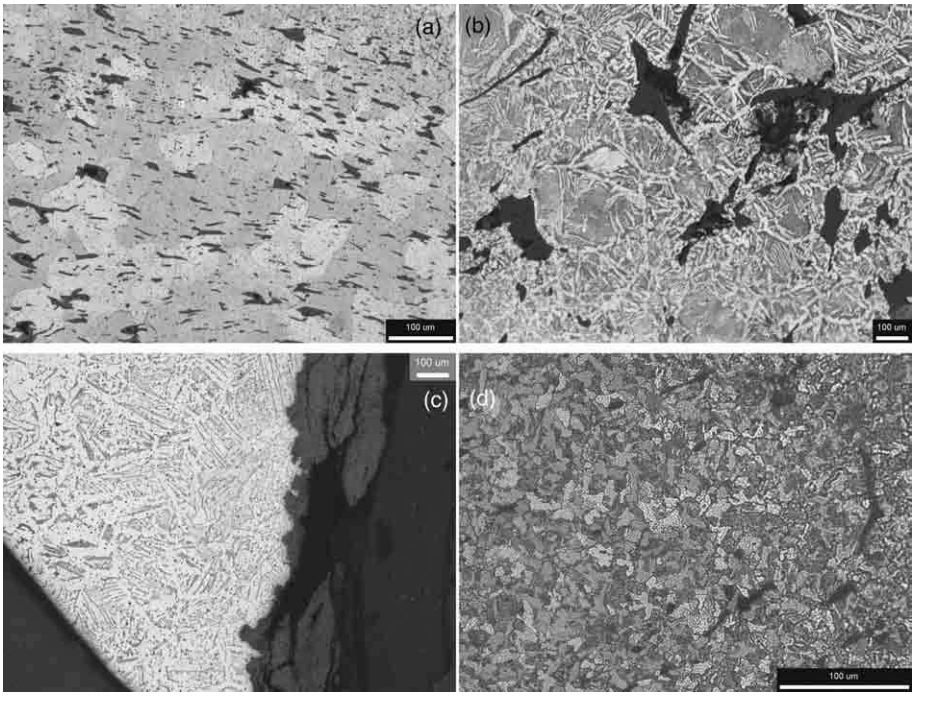

Figure 79: Microphotographs obtained on samples (a) T3 E, (b) T5 I, (c) T6 I, and (d) T6 E after nital etching.

justified by any specific technological choice. The most probable hypothesis is that there were two campaigns for installing reinforcing tie-rods in the transept gallery. The second one was probably done in order to replace some earlier tie-rods, produced by the bloomery process that were already in place in the transept itself (the case of the chapel could be different). These 'indirect' tie-rods were probably installed during the period mentioned by Viollet-le-Duc during which this part of the cathedral suffered damage as a result of the explosion of a neighbouring powder magazine. This needs to be confirmed by more detailed historical research. In any case, these 'indirect' tie-rods were probably put in the transept to replace ones that had been installed earlier. This was done after than the 15th century, most probably during the 19th century. The very regular surfaces of the 'indirect' tie-rod, unlike those of the bloomery one, could be explained by the bar having been made at a period during which the slitting mill made it possible to obtain long regular semi-products (Belhoste 1996).

Tie-rods that originated with the bloomery process (if the hypothesis of their having not been imported from areas where the direct process was still in use when the indirect process was in general use over the rest of Europe) seem to be earlier than the 15th century. They might have been put up during the building of this part of the cathedral, or shortly

afterwards. To obtain a definitive answer, an archaeological analysis of the components of the building in relation with the metallic elements must now be made. Finally, analytical results seems to show that decorative elements (T4SE) is totally different (e.g. the very high Mn content of the slag inclusions) and was put in the same time as the indirect tie-rods.

Table 12: Metallographic results obtained on the tie-rods of the southern arm of Soissons Cathedral.

Tie-rod	Average grain size (μm)	Slag inclusion volumic fraction (%)	Metallographic structure
T1 E	110	3	Equiaxed ferrite
T1 I	100	2	Equiaxed ferrite
T2 E	124	2	Equiaxed ferrite
T2 I	65	13	Equiaxed ferrite
T3 E	128	2	0.02-0.1% C (see **Fig. 80**) Ferritic-pearlitic
T3 I	33	2	0.02-0.1% C (see **Fig. 80**) Ferritic-pearlitic
T4 E	74	1	Ferritic
T4 I	100	1	0.02-0.1% C (see **Fig. 78**: c) Ferritic-pearlitic
T4SE	32	n.d;	Ferritic
T5E	Resists to etching	-	-
T5 I	70	8	0.1-0.4% C Ferritic-pearlitic
T6 E	75	8	0.02-0.2% C (see scheme) Ferritic-pearlitic
T6 I	80	2	0.02-0.3% C (see scheme)
T7 E	47	1	Ferritic
T7 I	69	7	0.02-0.1% C (see scheme) Ferritic-pearlitic
TN	61	10	Equiaxed ferrite
TsudE	80	5	Equiaxed ferrite
TSudI	96	4	Equiaxed ferrite

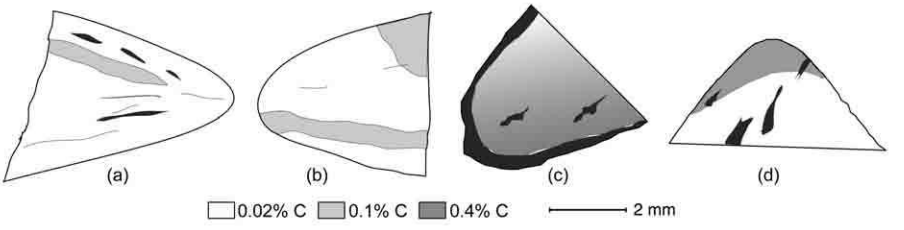

Figure 80: Schematic of the metallographic structures observed on the samples: (a) T3E, (b) T3I, (c) T5I, (d) T7I.

Another point that can be studied by slag-inclusion analysis is the homogeneity or heterogeneity of a given corpus coming from the bloomery process, by considering on the one hand the absolute contents of $P_2O_5^*$ and MnO^* and on the other the Non Reduced Compounds (NRC) ratios

($_{mass}\%Al_2O_3^*/_{mass}\%SiO_2^*$,$_{mass}\%K_2O^*/_{mass}\%CaO^*$,$_{mass}\%MgO^*/_{mass}\%Al_2O_3^*$). In the case of samples T3, T5, T6, and T7, these values are very homogeneous (see Table 11 and Fig. 81), which might indicate a common origin linked to a single workshop (i.e. reduction system) (Dillmann & L'Héritier, 2007).

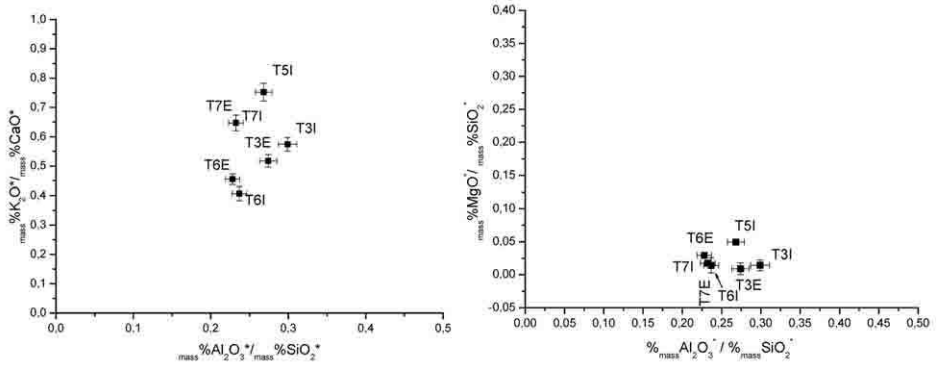

Figure 81: NRC ratios in slag inclusions of the tie-rods of the southern arm of the transept of the Soissons Cathedral.

Beauvais Cathedral

Analyses of the inclusions of samples taken in the attic of the cathedral (Table 14) show that four out of seven samples are related to the bloomery process. The three other are in the indeterminate domain on the abacus (Fig. 82).

Metallographic structures observed on samples from the attic are heterogeneous and more or less carburised (Fig. 83). Inclusion cleanliness is low or average.

Analytical results obtained on inclusions of samples coming from the flying buttresses are presented in Table 14 and on Fig. 84. Samples can be differentiated in three groups:

- Four samples linked to the indirect process. Some of them may have high phosphorus contents. These samples are C2NC1NAI, CN1CN2AC, CN2CN1AI and CN1BECN2
- Three samples can be linked to the bloomery process and have low levels of phosphorus: C2NC3NAI, C2NC3NCT et C2NEC1
- One sample (C2NBIO) is in the indeterminate domain of the abacus.

Samples of the first group have a mainly ferritic metallographic structure. In some of them, slag inclusions contain typical angular phases with

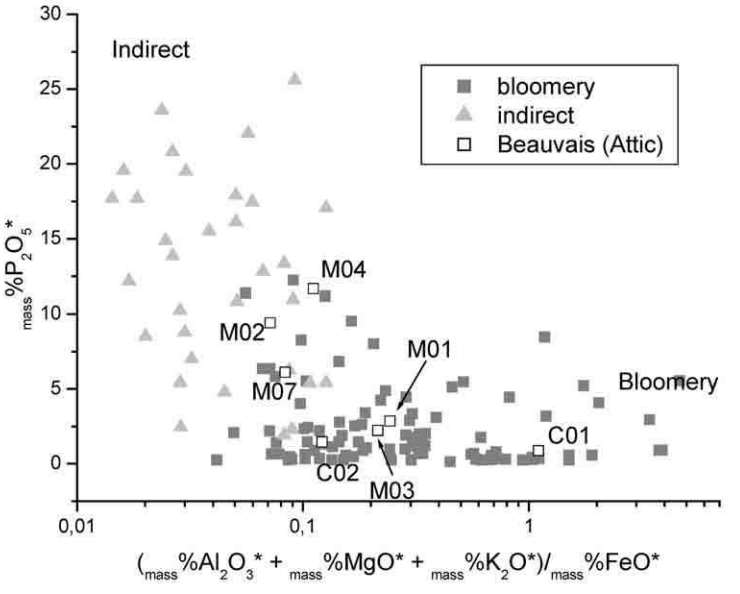

Figure 82: Ironmaking reduction process identification by slag-inclusion analyses (Dillmann & L'Héritier, 2007) of the samples taken in the attic of Beauvais Cathedral.

Table 13: Metallographic structures of the samples taken on Beauvais Cathedral.

Name	Structure	Grain size (μm)	% slag inclusion surface
C2NC3NBI	Equiaxed ferrite	90	9
C2NC3NCT	0.02-0.4% C carburized band in the centre	100	10
CN1BECN2	0.02-0.1% C ferritic-pearlitic Angular inclusions	90	8
C2NC1NAI	Ferritic Ghost structures	90	7
CN1CN2AC	Ferritic Angular inclusions	95	5
C2NC3NAI	0.02-0.5% C Ferritic-pearlitic	80	8
C2NEC1	0.1-0.3% C Ferritic-pearlitic	75	4
C2NBIO	Ferritic	100	6
C01	0.02-0.3% C Ferritic-pearlitic	70	5
C02	0.02-0.3% C Ferritic-pearlitic	75	8
M01	0.02-0.3% C Ferritic-pearlitic	65	7
M02	Ferritic	60	5
M03	0.02-0.4% C Ferritic-pearlitic	70	8
M04	Ferritic	90	9
M07	0.02-0.4% C Ferritic-pearlitic	60	7

high Ti and V contents that form during the refining stage of the indirect operating chain (Dillmann *et al.* 2002). The inclusion cleanliness of sam-

Table 14: Average weighted contents ($_{\text{mass}}\%$) (Dillmann & L'Héritier, 2007) of the inclusions of Beauvais Cathedral samples.

Name	MgO*	$Al_2O_3^*$	SiO_2^*	$P_2O_5^*$	SO_3^*	K_2O^*	CaO*	TiO_2^*	$V_2O_5^*$	$Cr_2O_3^*$	MnO*	FeO*
C2NC3NBI	< 0.25	2.56	15.18	3.48	< 0.25	0.63	1.68	< 0.25	< 0.25	< 0.25	1.12	74.36
C2NBIO	< 0.25	3.89	18.51	4.54	0.33	1.48	3.21	< 0.25	< 0.25	< 0.25	2.03	65.28
C2NC3NCT	0.90	10.64	45.92	0.57	0.67	3.61	4.90	< 0.25	< 0.25	< 0.25	0.94	30.90
CN1BECN2	0.34	0.93	15.59	5.42	0.72	1.40	5.59	0.30	0.71	0.29	0.46	67.87
C2NC1NAI	0.30	1.55	21.26	13.83	1.27	1.36	5.23	< 0.25	0.27	< 0.25	2.13	52.11
CN1CN2AC	0.33	0.82	13.65	5.25	0.68	1.25	5.06	< 0.25	0.61	0.28	0.37	70.93
C2NC3NAI	0.49	5.16	29.37	0.92	0.48	1.55	1.34	< 0.25	< 0.25	< 0.25	0.99	58.76
C2NEC1	1.94	16.15	56.77	1.90	0.72	2.44	3.43	0.37	< 0.25	< 0.25	2.88	12.17
M01	0.72	7.83	33.69	2.86	0.79	2.44	3.97	0.26	< 0.25	< 0.25	1.63	45.26
M02	0.32	2.90	21.62	9.41	0.74	1.16	1.50	< 0.25	< 0.25	< 0.25	0.47	61.10
M03	0.88	6.07	33.20	2.24	0.52	2.53	3.85	0.26	< 0.25	< 0.25	5.80	44.10
M04	< 0.25	4.71	19.80	11.68	0.65	1.26	4.13	< 0.25	< 0.25	< 0.25	0.89	55.95
M07	0.26	3.81	19.81	6.12	0.54	1.28	2.23	< 0.25	< 0.25	< 0.25	1.02	64.19
C01	1.36	10.88	57.74	0.87	1.14	4.63	4.12	< 0.25	< 0.25	< 0.25	3.04	15.26
C02	0.41	4.93	26.3	1.45	0.77	1.65	4.60	< 0.25	< 0.25	< 0.25	0.99	57.50

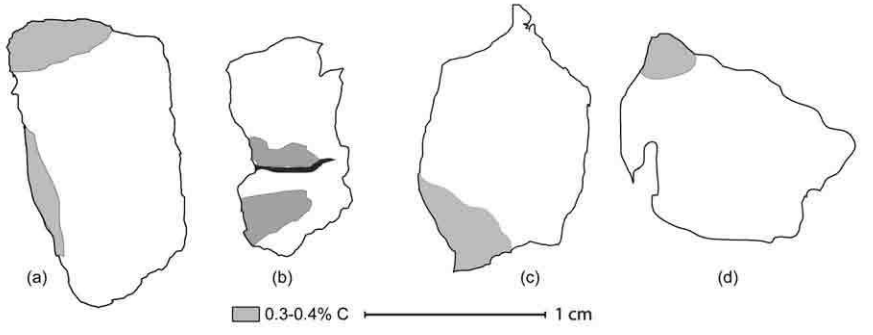

Figure 83: Schematics of the metallographic structures observed on samples (a) M01, (b) M03, (c) M07, and (d) C02 taken in the attic of Beauvais Cathedral.

ples of this group is low. Samples linked to the bloomery process (second group) also have low inclusion cleanliness, but they present structures that are more heterogeneous as far as the carbon content is concerned (Fig. 85).

It appears clearly that samples taken from the flying buttresses associated with the indirect process were unquestionably taken on tie-rods put up in the cathedral during the 18th century campaigns and are contemporary of the '1714' graffiti. The microstructures of these samples is that of a phosphoric iron with a ferritic structure and with poor inclusion cleanliness, which is relatively classic for samples of that period deriving from the indirect process. By contrast, the three samples linked to the bloomery process were probably not put up in the cathedral in the same period. It can then be deduced that they were put between the flying buttresses at a period during which the bloomery process is used in the area of Beauvais (i.e. before the 14th century, and most probably during the building of the cathedral during the 13th century). This discovery is important because, despite the fact that it is not known if the number of

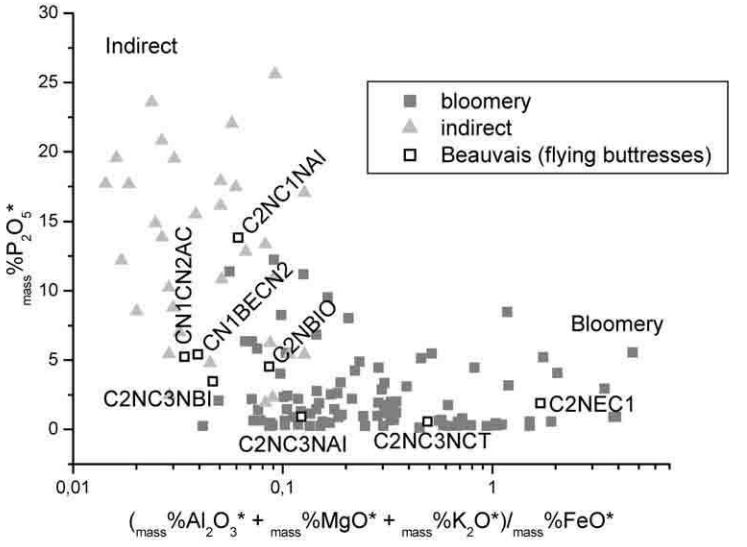

Figure 84: Ironmaking reduction process identification by slag-inclusion analysis (Dillmann & L'Héritier, 2007) of the samples taken between the flying buttresses of Beauvais Cathedral.

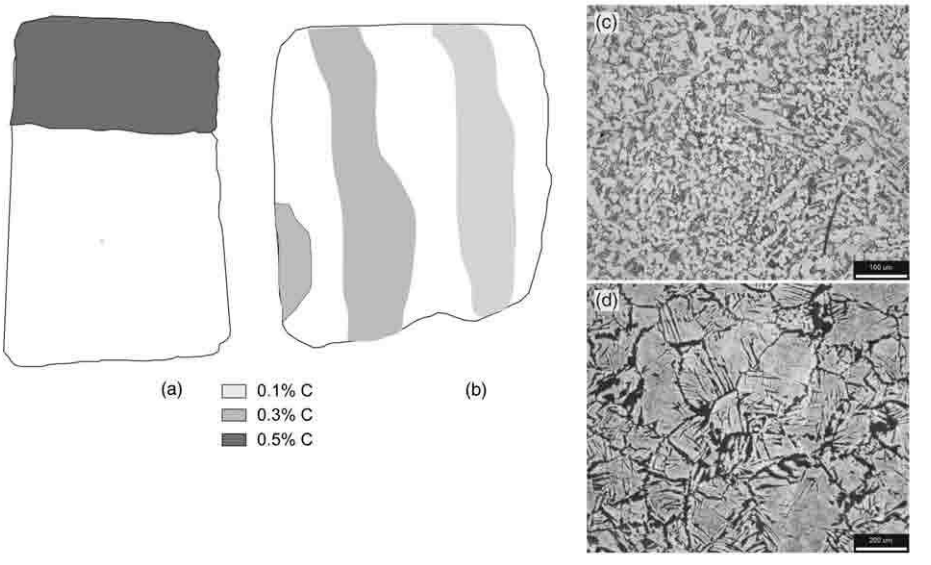

Figure 85: Schematics of the metallographic structures observed on samples (a) C2NC3NAI and (b) C2NECI and optical microphotographs after nital etching on (c) C2NECI and (d) C2NC3NCT. All these samples are linked to the bloomery process.

tie-rods was smaller than it is in the modern period, it seems that ferrous alloy components were used to reinforce the structure of the building from the very beginning of the monument.

These hypotheses are confirmed by the fact that the chain in the attic is also linked to the bloomery process and therefore installed there earlier than the 14th century, most probably when the monument was being built. The same applies to the hooks on the walls in the attic, which could have been put there to fasten tie rods during building works (Taupin 1996).

Amiens Cathedral

Table 15 shows that, with the exception of samples located in the undetermined zone of the abacus (AmLXXXIV and Agr74 T), they can be divided in two groups (Fig. 86), based on the reduction process involved (Fig. 86). Fig. 87 /Plate XXIV/ shows these results relative to the position of the artefacts in the triforium.

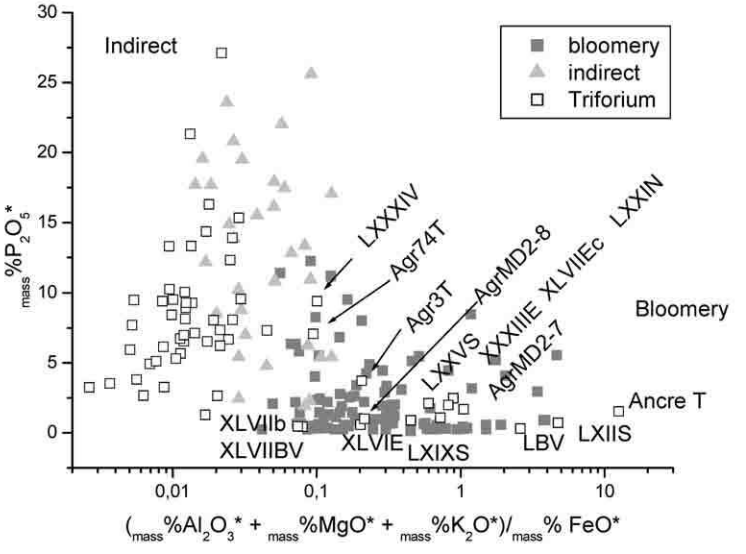

Figure 86: Identification of ironmaking reduction processes by slag-inclusion analyses (Dillmann & L'Héritier, 2007) of the samples of the triforium of Amiens Cathedral.

It is clear that almost all the 'standardized' links of the chain are made from a metal produced by the indirect process. One single link does not follow this rule: the rod AmLXXI in the southern arm of the transept is in the undetermined zone in the abacus. The 22 other 'standardized' samples comes from the indirect process. Apart from the LXXI rod, the bloomery process seems to be systematically linked to non-standard elements – smaller links or different forms of link, linking the chain extremity and a crow's foot (AmXLVI), crow's feet (AmXLVII), and the vertical bar fasting a crow's foot to the wall (AmXLVII). It should also be noted that the ends of some part of the chain were made using iron from the bloomery

Table 15: Average weighted contents ($_{\text{mass}}\%$) (Dillmann & L'Héritier, 2007) of the inclusions of the Amiens Cathedral samples.

NOM	MgO^*	$Al_2O_3^*$	SiO_2^*	$P_2O_5^*$	SO_3^*	K_2O^*	CaO^*	TiO_2^*	$V_2O_5^*$	$Cr_2O_3^*$	MnO^*	FeO^*
Am IV W	0.04	0.07	8.78	10.25	0.31	0.60	3.55	0.11	0.19	0.06	0.68	75.13
Am VI E	0.04	0.15	6.06	2.66	0.27	0.36	1.97	0.22	0.19	0.11	0.27	87.40
Am VI W	0.30	0.34	11.07	1.28	0.22	0.72	3.51	0.19	0.21	0.14	0.50	81.29
Am VIII W	0.03	0.12	10.31	5.12	0.42	0.46	2.71	0.16	0.14	0.10	0.61	79.54
Am VIII E	0.15	0.21	12.99	5.67	0.30	0.49	3.67	0.17	0.18	0.13	0.57	75.33
Am X W	0.41	0.12	8.67	7.13	0.15	0.59	3.06	0.13	0.15	0.09	0.37	78.23
Am X E	0.19	0.23	12.75	6.54	0.34	0.84	4.79	0.15	0.18	0.07	1.06	72.72
Am XII W	0.11	0.30	15.40	6.55	0.27	0.45	3.26	0.16	0.16	0.07	1.09	72.00
Am XII E	0.30	0.28	9.79	21.33	0.60	0.27	1.92	0.09	0.10	0.07	0.36	64.44
Am XIV E	0.55	0.42	14.40	2.65	0.29	0.59	3.14	0.11	0.11	0.08	0.19	77.04
Am XIV W	0.34	0.49	18.13	12.32	0.32	0.71	5.04	0.17	0.13	0.09	0.75	61.35
Am XVIN	3.54	15.27	57.16	0.33	0.34	8.45	9.44	0.29	< 0.25	< 0.25	2.25	2.63
Am XVIII N	0.06	0.00	11.86	5.95	0.07	0.33	1.78	0.08	0.05	0.08	0.75	78.80
Am XVIII S	0.16	0.38	19.19	6.23	0.35	0.87	4.85	0.14	0.07	0.04	1.24	66.36
Am XX N	0.84	0.67	18.08	7.32	0.41	1.39	5.76	0.14	0.12	0.10	0.41	64.27
Am XX S	0.09	0.23	12.27	9.28	0.26	0.66	3.57	0.14	0.15	0.09	0.74	72.38
Am XXIV	0.36	0.27	15.05	14.36	0.58	0.47	2.79	0.10	0.09	0.05	0.72	64.64
Am XXVIII patte	0.06	0.21	11.22	8.16	0.46	0.64	3.10	0.15	0.09	0.09	0.58	75.10
Am XXX N	0.47	0.27	12.05	16.29	0.74	0.43	2.52	0.04	0.10	0.07	0.87	65.75
AmXXXI S	< 0.25	0.54	20.54	15.34	0.87	0.87	3.16	< 0.25	< 0.25	< 0.25	0.36	57.42
AmXXXIIIE	2.43	7.35	44.92	1.09	0.75	6.07	10.44	< 0.25	< 0.25	< 0.25	3.96	21.91
Am XXXIV patte	0.01	0.06	4.41	3.53	0.21	0.26	1.41	0.15	0.10	0.08	0.32	89.27
Am XXXIV W	< 0.25	0.30	12.45	13.32	0.59	0.36	2.92	0.11	0.08	0.04	0.55	68.50
Am XXXIV E	0.46	0.42	11.97	8.06	0.58	0.54	2.65	0.06	0.09	0.06	0.48	73.89
Am XLII Patte	0.26	0.39	14.73	8.08	0.26	1.16	4.40	0.16	0.12	0.11	0.56	69.52
Am XLII W	0.26	0.14	7.66	6.15	0.28	0.31	1.87	0.12	0.06	0.07	0.33	82.37
Am XLVI E	0.24	7.14	21.78	0.58	0.33	4.25	4.94	0.24	0.11	0.08	2.28	57.83
Am XLVII Ec	3.40	7.66	44.37	1.98	1.18	5.30	10.42	< 0.25	< 0.25	< 0.25	4.13	19.90
XLVII B	< 0.25	2.56	23.62	0.43	0.27	2.26	3.86	< 0.25	< 0.25	< 0.25	2.62	63.63
Am XLVIIBV	0.27	2.46	22.36	0.46	0.31	2.02	4.84	< 0.25	< 0.25	< 0.25	2.51	64.27
AmXLIXS	< 0.25	0.47	16.57	27.12	1.10	0.38	2.70	< 0.25	< 0.25	< 0.25	0.69	50.07
Am L BV	2.29	16.76	53.33	0.32	< 0.25	5.40	9.28	0.34	< 0.25	< 0.25	1.47	9.42
Am LW	< 0.25	< 0.25	12.87	8.95	0.51	0.40	2.39	< 0.25	< 0.25	< 0.25	0.50	73.49
AM LII patte	0.03	0.03	6.26	3.81	0.18	0.42	2.11	0.11	0.14	0.08	0.44	86.25
AmLII W	0.01	0.18	10.31	9.41	0.45	0.45	2.50	0.14	0.13	0.09	0.68	75.50
Al LIV Patte	0.01	0.03	9.32	7.69	0.27	0.37	1.99	0.12	0.12	0.08	0.53	78.78
Am LIV E	0.14	0.14	10.03	6.74	0.30	0.59	3.19	0.12	0.14	0.08	0.65	77.69
Am LVIPatte	0.08	0.15	9.51	13.31	0.46	0.46	2.40	0.10	0.15	0.06	0.68	72.48
Am LVI E	0.26	0.57	15.05	9.56	0.43	1.13	5.12	0.17	0.21	0.10	1.12	66.08
AmLVIIIE	< 0.25	< 0.25	11.30	8.44	0.42	< 0.25	2.21	< 0.25	< 0.25	< 0.25	0.37	76.19
Am LX Patte	0.13	0.31	15.73	6.69	0.56	1.26	4.14	0.15	0.14	0.09	0.62	70.01
Am LX S	0.00	0.07	8.27	9.50	0.56	0.35	2.10	0.15	0.11	0.08	0.60	78.09
Am LXII corrigé S	3.87	14.86	53.16	0.73	0.55	7.49	10.60	0.36	0.02	0.09	1.18	5.51
Am LXIIN	0.31	0.55	17.72	7.37	0.52	0.59	3.94	< 0.25	< 0.25	< 0.25	0.28	68.06
Am LXIII-S	0.06	0.12	8.66	4.92	0.28	0.39	1.91	0.15	0.17	0.14	0.34	82.44
Am LXVI S	0.00	0.00	1.84	3.26	0.12	0.06	0.45	0.00	0.05	0.03	0.16	23.46
LXVII S	< 0.25	< 0.25	11.68	6.98	< 0.25	0.42	2.83	< 0.25	< 0.25	< 0.25	0.30	76.83
AmLXIX N	0.95	11.77	31.39	0.89	0.50	5.69	5.25	< 0.25	< 0.25	< 0.25	1.75	40.90
AmLXXIN	2.48	2.64	61.04	2.47	0.59	3.86	15.04	< 0.25	< 0.25	< 0.25	0.59	10.07
AmLXXIVNb	< 0.25	0.26	7.90	5.30	0.34	0.35	1.74	< 0.25	< 0.25	< 0.25	0.31	81.98
AmLXXV S	1.64	12.12	41.64	2.12	0.61	3.70	6.61	0.33	< 0.25	< 0.25	1.33	29.22
AmLXXVI W	< 0.25	0.28	14.95	10.05	0.46	0.32	2.24	< 0.25	< 0.25	< 0.25	0.54	70.39
AmLXXVIIW	< 0.25	< 0.25	6.50	3.27	0.28	< 0.25	2.29	< 0.25	< 0.25	< 0.25	< 0.25	86.43
AmLXXXIE	< 0.25	0.68	21.41	13.90	0.79	0.57	3.69	< 0.25	< 0.25	< 0.25	0.33	57.65
AmLXXXIV W	1.40	1.61	32.18	9.41	1.03	1.35	6.89	0.26	0.42	< 0.25	1.50	43.41
AmLXXXVIIW	< 0.25	< 0.25	11.75	9.53	0.31	< 0.25	2.46	< 0.25	< 0.25	< 0.25	0.26	74.59
Am ancre A	< 0.25	0.29	11.19	9.30	0.70	0.37	2.53	< 0.25	< 0.25	< 0.25	0.29	74.60
Ancre T	3.41	16.93	60.49	1.53	1.13	4.29	6.32	0.27	< 0.25	< 0.25	0.68	1.96
Agrafe 74	0.29	4.12	23.33	7.08	2.39	1.15	2.05	< 0.25	< 0.25	< 0.25	< 0.25	58.81
Agr3T	0.56	6.44	33.77	3.73	0.30	2.66	4.30	< 0.25	< 0.25	< 0.25	0.53	47.05
Agr MD2-8	0.58	8.14	37.39	1.01	0.68	1.29	2.89	0.27	< 0.25	< 0.25	< 0.25	46.74
Am Agr MD2-7	2.45	12.16	50.80	1.68	0.54	2.89	11.10	0.48	< 0.25	< 0.25	< 0.25	16.66
AmTS01	2.59	3.64	32.07	2.54	1.39	2.84	7.21	< 0.25	< 0.25	< 0.25	11.97	34.14
AmTS02	3.03	2.71	35.73	1.16	0.76	2.90	7.67	< 0.25	< 0.25	< 0.25	10.97	34.42
AmTS03	5.40	5.77	52.40	0.37	1.05	3.91	8.57	< 0.25	< 0.25	< 0.25	7.08	14.53
AmTS5	0.49	10.14	27.25	0.42	0.34	4.58	4.17	0.27	< 0.25	< 0.25	< 0.25	51.56
TS06	1.84	3.65	46.20	2.26	0.70	3.75	4.10	< 0.25	< 0.25	< 0.25	9.37	27.32
AmTS08	2.62	8.91	46.77	0.75	0.35	5.95	8.68	0.46	< 0.25	< 0.25	9.93	15.06
AmTS9	3.47	4.53	37.09	1.38	1.12	2.50	5.89	< 0.25	< 0.25	< 0.25	8.99	34.47
AmTS10	0.85	8.70	24.72	3.25	2.27	3.29	3.92	< 0.25	< 0.25	< 0.25	< 0.25	51.60

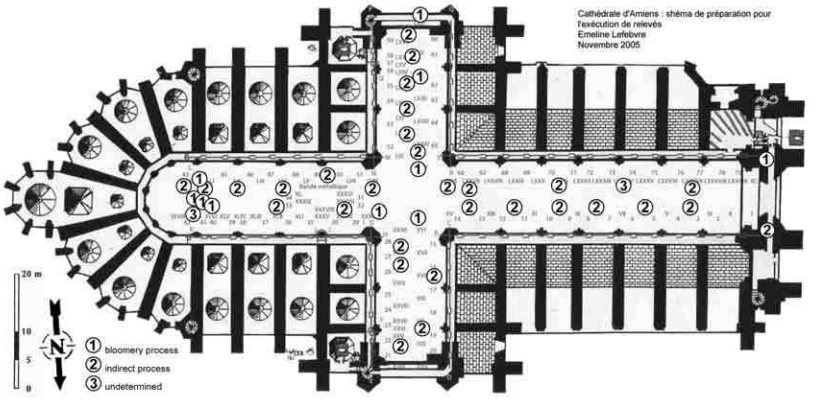

Figure 87: Position of the sampled links in the triforium of Amiens Cathedral and the ironmaking process as determined by slag-inclusion analysis 1: bloomery process. 2: indirect process, 3: undetermined.

process. This is the case for the chains of the northern part of the choir and in the southern arm of the transept on the western side. More surprisingly, anchors T and A from the south and north chains of the nave are linked with the bloomery and the indirect processes respectively. It therefore seems that, although not applied systematically for all parts of the chain, iron from the bloomery has been selected for some chain ends (anchors, crow's feet). This is completely borne out in the northern part of the choir.

For samples linked with the bloomery process, it is possible to compare the NRC ratios and the $P_2O_5^*$ and MnO^* contents. Several groups with homogeneous origins can then be distinguished (see above). Analysis show that, when only the $P_2O_5^*$ and MnO^* contents of the slag inclusions are taken into account, it is not possible to distinguish different groups (Fig. 88). This does not, of course, mean that they have the same origin: this feature (average or low levels of $P_2O_5^*$ and MnO^* in the slag inclusion) is relatively common for ferrous alloys produced by the direct process.

CNR ratios are more eloquent. Fig. 89 makes it possible to distinguish three samples groups clearly. The first one consists of a single example (AmLXXIN). This is the only 'standardized link made from bloomery iron. The second group consists of samples AmXLVIIb, AmBV, AmEc, and AmXXXIIIE. It is interesting to note that these pieces are all elements used for securing the two ends of the chain in the northern part of the choir. AmXLVIIb and AmEc are both crow's feet, AmBV is a vertical rod, and AmXXXIIIE is an anchor at the east side of the chain. It can thus be reasonably supposed that, in this part of the chain, the elements derived from the bloomery process used at both extremities have the same origin

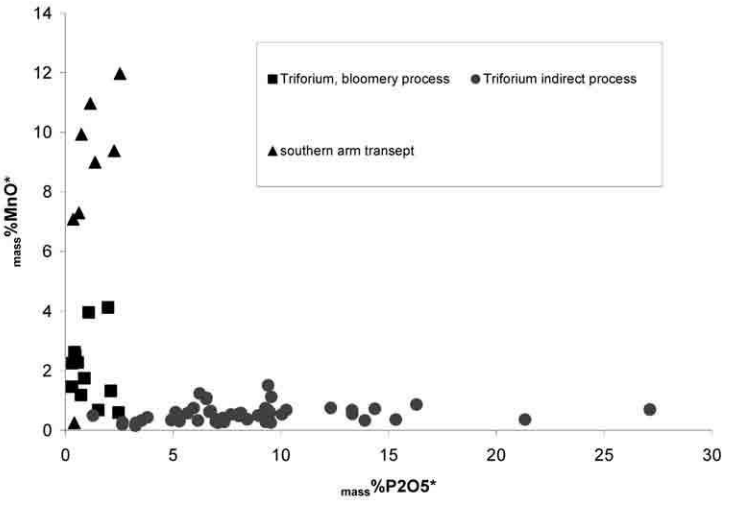

Figure 88: Average $P_2O_5^*$ and MnO* weighted contents in the links of the triforium chain of Amiens Cathedral.

and were put up in the triforium by the same craftsman. This craftsman maybe choose to put bloomery iron at the extremity, the rest of the chain being realised made from indirect iron in 'standardised' elements. The third group, which is more heterogeneous, is not necessarily made up of artefacts of the same origin as the iron elements employed at other chain ends.

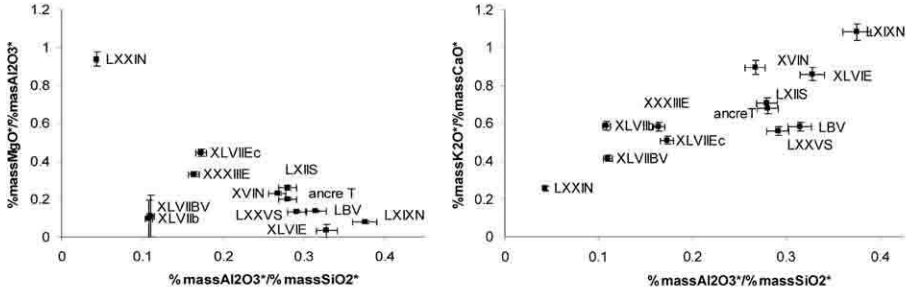

Figure 89: $_{\text{mass}\%}Al_2O_3^*/_{\text{mass}\%}SiO_2^*$, $_{\text{mass}\%}Al_2O_3^*/_{\text{mass}\%}MgO^*$ and $_{\text{mass}\%}K_2O^*/_{\text{mass}\%}CaO^*$ in the slag inclusions of the bloomery iron links of the triforium chain of Amiens Cathedral.

As far as the metallographic structure is concerned, all the indirect process samples (%C < 0.02) contain significant amounts of phosphorus, as indicated by ghost structures (Fig. 90). At the other hand, artefacts linked to the bloomery process are made of ferrous alloys with heterogeneous carbon contents (from 0.02% to 0.8%). This heterogeneity is in good agreement with observations already made in other studies on bloomery

iron: it is due to initial inhomogeneities in the bloom caused by heterogeneous thermodynamic and kinetic conditions in the shaft furnace.

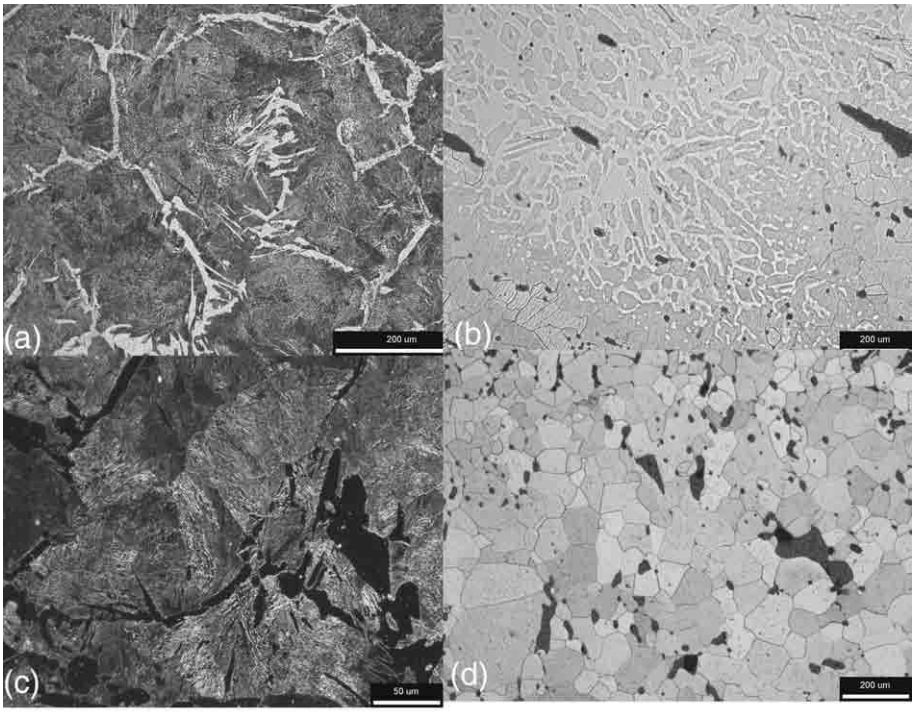

Figure 90: Microphotographs of samples taken on triforium chain links of Amiens Cathedral: (a) LXIIIS – ferritic-pearlitic Widmanstätten structure, bloomery process; (b) XIV W – ferrite with ghost structures, indirect process; (c) XVIN – ferritic-pearlitic Widmanstätten structure, bloomery process; (d) XXVIIIP – ferrite, indirect process.

To summarize, in the Amiens triforium chain the 'standardized' elements are the result of ore reduction using the indirect process. The metal is phosphorous iron containing a significant number of slag inclusions. This process seems to exclude an origin linked with Spain, where during the 15th century only the bloomery process was in use. Some non-standardized links used at the chain ends (particularly in the northern part of the choir) are made from bloomery iron. There was evidence of different origins, as a function of the position in the chain. Materials of the same origin were used in the northern part of the choir. This is in good agreement with the hypothesis of craftsmen putting up the 'standardized' links of the chain, which had been made elsewhere, and making special pieces at the ends of the chains, using bloomery iron (perhaps from Spain). However, despite the fact that the bloomery process is compatible with a Spanish origin at the period under consideration, it is not possible by major-element slag-inclusion analysis alone to confirm this origin. In order to take this work

further trace-element analyses are needed.

Clamps from the triforium are linked with the bloomery process, as indicated by results obtained on the 3T sample. This is in good agreement with the archaeological analysis, which claimed that these clamps were put in the triforium during the building of the cathedral. Despite the fact that clamps from the side of the transept are linked to the bloomery process, there is nothing that indicates that they were inserted during the building of the monument or during later works (but probably before the 14th century).

Fig. 91 shows the reduction process for samples taken on the chain located in the southern arm of the transept. It is clear that all the links and anchors of this chain are linked with the bloomery process. However, it is significant that the highest MnO* slag inclusion content (Fig. 88) when compared with the one of the links of the triforium chain reveal a different origin. There are only two artefacts without this high MnO* content – the vertical rods TS05 and TS10, fastening a part of the anchors. This completely confirms by the NRC ratios (Fig. 92) that are, for these latter examples, clearly different from those formed by the other artefacts.

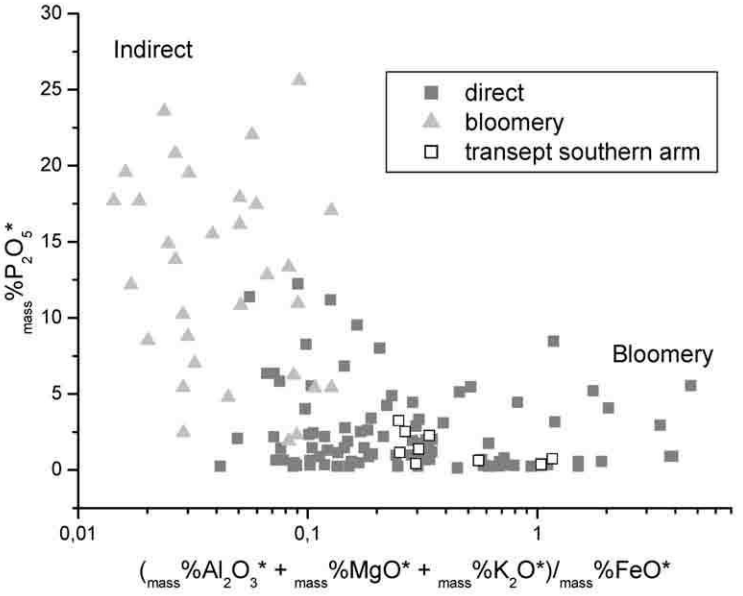

Figure 91: Ironmaking reduction process identification by slag-inclusion analyses (Dillmann & L'Héritier, 2007) of the samples of the chain of the southern arm of the Amiens Cathedral transept.

The fact that this chain is linked with the bloomery process poses a certain number of questions. Indeed, that point, when a different slag inclusion composition is taken into consideration, seems to indicate that

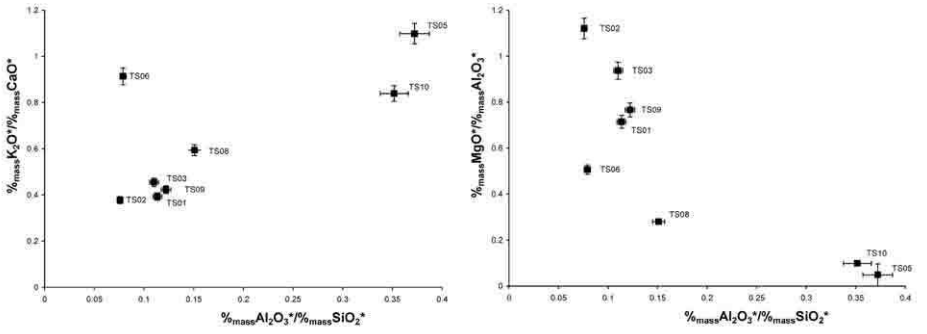

Figure 92: $_{mass\%}Al_2O_3^*/_{mass\%}SiO_2^*$, $_{mass\%}Al_2O_3^*/_{mass\%}MgO^*$ and $_{mass\%}K_2O^*/_{mass\%}CaO^*$ in the slag inclusions of samples from the chain of the southern arm of the transept of Amiens Cathedral.

the chain of the triforium and the present one have a different origin and were not installed in the cathedral at the same period. Historical data indicates that 1503 was a time of important repair work in the southern arm of the transept. One hypothesis might be to date the chain from this period. However, the bloomery process was not in use at that time in the Amiens area, where the indirect process was in general use in the 16th century. Thus, if this chain was put in the cathedral in 1503, it could be made of *fer d'Espagne*, made from a high-manganese ore. Unfortunately, unlike the triforium chain, there is no historical source that explicitly mentions that in the southern part of the transept. Another hypothesis could be the chain was installed in the cathedral at an earlier period when the bloomery process was in use in Picardy. However, this latter hypothesis seems to contradict the architectural analysis.

Conclusion

The metallographic and slag inclusion analysis results obtained in the present study lead to several comments on the material quality and the role of the ferrous material in the present context. The first comment relates to ferrous alloys coming from the indirect process. They all show the same metallographic characteristics: they are consist only of ferrite, sometimes containing significant quantities of phosphorus. On the fifty samples analysed for this study derived from the indirect process, only one sample contain slightly carburised zones up to $0.1_{mass}\%$ C. These observations completely confirm that already made in our earlier studies: ferrous alloys coming from the indirect process seems, as far as carbon content is concerned, to be much more homogeneous. Moreover, when no

specific carburization is needed by virtue of the function of object (as is the case for architectural materials), it is homogeneous ferritic iron, which is easily made in the refining hearth. This is different in the case of the bloomery process, for which, even if no carburized materials are required, this parameter is difficult to control in the shaft furnace. It is not therefore rare in artefacts from this process to find carburized zones randomly distributed in the material or in the form of bands, the result of hot forging. This is the case in the present study.

This homogeneity of carbon content, which seems to be a characteristic of the indirect process, is not verified for other parameters such as phosphorus content or slag-inclusion or grain-size distribution. It is clear that the craftsmen working in the building of cathedrals did not try to use a particular alloy quality. All the microstructure used in architecture (apart from the particular case of the Palais des Papes in Avignon (Dillmann *et al.* 2004)) is 'low-quality'. This notion of 'quality', however, is a very relative one and depends on the final use of the metal. To forge a blade or armour it is necessary to control the distribution and size of slag inclusions and the carbon content, but that is not the case for tie-rods in cathedrals. Although they only very rarely broke from the time they were installed in the cathedrals, these metal elements seem nevertheless to have been perfectly dimensioned in relation to the effort they supported and their microstructure.

The results obtained in this paper on the identification of ironmaking processes though light on the use of ferrous alloys to reinforce medieval monuments. For Soissons and Beauvais Cathedrals it seems that the presence of bloomery iron can be linked to the use of this material during the construction of the building, or at least very early in its history. For the southern arm of the Soissons transept these elements are the tie-rods that pierce the Gothic vault, whilst at Beauvais Cathedral they are hooks in the attic that may have been used to provide temporary support for the walls during construction, and also a chain going through the attic, which still today plays a role in the building, and, last but not least, massive tie-rods between the flying buttresses. These latter pieces were perhaps not so numerous during the 13th century than in the modern period, but it seems that, since the first years of the cathedral life, iron has played an important role in the structure of the monument.

For Amiens Cathedral the period during which the small chain in the southern arm of the transept was inserted is difficult to determine. It is, moreover, important to clarify the fact that bloomery iron was found at this location in the cathedral. As far as the triforium chain is concerned, which is well dated by historical sources, the analytical results are very interesting. Indeed, this chain has been considered up to now as being

made of *fer d'Espagne*, i.e. bloomery iron coming from the south of France or the Iberian Peninsula. It is in fact not made from this material but from iron made by the indirect process. This chain is one of the rare French examples of early 15th century indirect iron used in architecture. Historical sources show that the indirect process was established in the area at this period, but no archaeological occurrence of materials produced with this process were hitherto known. The discrepancy with historical sources on the triforium chain must be clarified in the future. The fact that, in order to assemble these indirect iron standardized links, which were probably made using a water-driven hammer, bloomery iron was used at the ends of some chains, throws light on how craftsmen assembled and installed the chain in the triforium. The picture emerges of a local craftsman put links produced elsewhere into the triforium but used a different material to create anchors and 'home-made' links to fasten the chain to the stone structure. This is the case in the north part of the choir, but not in the other part of the triforium. How can this be explained? Were there different craftsmen working in other parts of the triforium with other ways of working? This is a strong possibility.

Acknowledgements

Thanks to Emeline Lefebvre, Arnaud Timbert, Maxime L'Héritier, and Judith Monnier for helping to collect samples, for chemical, archaeological, and historical studies, and for their stimulating scientific discussions.

References

Amoudruz, F. et al. 1997: Amoudruz, F., Chapelot, J. & Clement, S. 1997, 'Les éléments métalliques (fer et plomb) dans l'architecture du donjon du château de Vincennes. *Etude préliminaire', Vincennes, Equipe de Recherche sur le château de Vincennes et la banlieue est.*

Barret, E. et al. 2006: Barret, E., Bernardi, P., Dillmann, P., Markiewicz, C., Mignon, J.-M. & Vingtain, D. 2006, 'Recherches sur le Palais des Papes d'Avignon', *Les dossiers de l'Archéologie* 314, 68-71.

Belhoste, J.-F. 1996, 'Fabrication et mise en oeuvre du fer dans la construction (XIIIe-XIXe siècles)', *Bulletin Monumental* 13, 8-17.

Bernardi, P. & Dillmann, P. 2005, 'Stone skeleton or iron skeleton: The provision and use of metal in the construction of the Papal Palace

at Avignon in the 14th century', in R. Bork (ed.), *De Re Metallica. The uses of metal in the Middle Ages* (Ashgate), 297-316.

Clément-Charpentier, S. 2001, 'Le rôle des éléments métalliques dans la conception du donjon de Vincennes', in O. Chapelot (ed.), *Du projet au chantier. maîtres d'ouvrages et maîtres d'oeuvre aux XIVe-XVIe siècles* (Paris), 405-431.

Dillmann, P. & L'Héritier, M. 2007, 'Slag inclusion analyses for studying ferrous alloys employed in French medieval buildings: supply of materials and diffusion of smelting processes', *Journal of Archaeological Science* 34, 1810-1823.

Dillmann, P. et al. 2003: Dillmann, P., Bernardi, P. & Fluzin, P. 2003, 'Use of iron for the building of medieval monuments. The Palais des Papes in Avignon and other French buildings', in *Archaeometallurgy in Europe* (Milan), 199-208.

Dillmann, P. et al. 2004: Dillmann, P., Bernardi, P. & Fluzin, P. 2004, 'Iron in medieval monuments. Metallographic analysis of irons coming from the Palais des Papes in Avignon', *La Revue d'Archéométrie* 27, 183-192.

Dillmann, P. et al. 2002: Dillmann, P., Fluzin, P. & Chevalier, P. 2002, 'Determination of ironmaking process using synchrotron microprobe', *British Archaeological Reports International Series* 1043 (II), 327-334.

Lefebvre, E. 2006, 'La place et le rôle des métaux dans l'architecture gothique à travers l'exemple de la cathédrale d'Amiens. Étude de cas: le chaînage du triforium de la cathédrale d'Amiens', *Archéologie médiévale* (Amiens).

L'Héritier, M. et al. 2005: L'Héritier, M., Juhin, A., Dillmann, P., Aranda, R. & Benoit, P. 2005, 'Utilisation des alliages ferreux dans la construction monumentale du Moyen Age. État des lieux de l'avancée des études métallographiques et archéométriques', *La Revue d'Archéométrie* 29, 117-132.

Pokorny, J. & Pokorny, A. 1994, 'Métallographie. Techniques de l'Ingénieur', in *M 90* - volume MB, 1-52.

Taupin, J.-L. 1996, 'Le fer dans les cathédrales', *Monumental* 13, 18-27.

Vega, E. et al. 2002: Vega, E., Dillmann, P. & Fluzin, P. 2002, 'Contribution à l'étude du fer phosphoreux en sidérurgie ancienne', *La revue d'Archéométrie* 26, 197-208.

Viollet-Le-Duc, E.-E. (ed.) 1854, *Dictionnaire raisonné de l'architecture française du XIe au XVe siècle* (Paris).

Examples of involvement of archaeometallurgy into archaeological, historical and historical-technological research

Archaeological metallography in Russia: historiographic notes
by V.I. Zavyalov

Archaeometallography in solving historical and cultural problems
by V.I. Zavyalov, L.S. Rozanova and N.N. Terekhova

The multidisciplinary approach (archaeology and archaeometry) to bloom-smithing activities in France: examples of results from the last 20 years
by P. Fluzin, S. Bauvais, M. Berranger, G. Pagès and P. Dillmann

Archaeological metallography in Russia: historiographic notes

V.I. Zavyalov

Metallography has been actively used to study ancient metal artefacts for more than sixty years. It was B.A. Kolchin who formulated the main principles of the metallographic method for archaeological material. Among the scientists originated the new method of archaeological material research was Professor Radomír Pleiner.

The main stages in the development of archaeological metallography and some achievements in studying the craft of the ancient blacksmith by Russian scientists are examined in this paper. The list of publications on East European ferrous metallurgy includes over 500 titles. Most of the articles and monographs were dedicated to the craft of Slavic and Old Russian blacksmiths. A considerable part of the work is also devoted to another important problem – the origin of ferrous metallurgy and metalworking in Eastern Europe.

Blacksmith craft - History of archaeometallography - Metallographic research - Scientific literature

Metallography has been actively used to study ancient metal artefacts for more than sixty years[3]. It was B.A. Rybakov who justified the need to apply special natural scientific methods to the study of the ancient crafts (Rybakov 1948, 237). The main principles of using of the metallographic method for archaeological material were formulated by B.A. Kolchin in the late 1940s and early 1950s. He outlined the capabilities of the method and the circle of questions that could be resolved by it, and was the founder of a new school in the historical studies of the blacksmith's craft – archaeological metallography (archaeometallography).

Among the scientists who were the originators of the new method of archaeological material research was Professor Radomír Pleiner, whose studies have contributed greatly to the world literature on the history of metallurgy and the blacksmith's craft, and today no serious work on archaeometallurgy is complete without references to them. Radomír Pleiner

[3]The present article only covers subjects related to the problems of ferrous metallurgy and metalworking.

had a profound respect for Boris Kolchin. This article will consider the main historiographic aspects of Russian archaeometallography. In this way I would like to express my gratitude to my teachers – Boris Kolchin, who helped me to come out of my shell as a scientist, and Radomír Pleiner whose books and articles I refer to continually.

My objective is not to produce a comprehensive essay on the history of archaeometallography in the East European countries – that is a subject of a special work that would be far beyond the scope of a single article. Making no pretence for complete and full consideration of the subject, I shall concentrate my attention on the main stages in the development of archaeological metallography and some achievements in studying the craft of the ancient blacksmith in Russian science.

The list of publications on the ancient ferrous metallurgy of Eastern Europe includes over 500 titles. It is interesting to trace distribution of works during the last six decades year by year (Fig. 93). The diagram shows a skewed but constantly growing number of publications on archaeometallography. Before the early 1960s it was a matter of no more than single works, which is not surprising because the majority of them were by a single author – Boris Kolchin. These very works, however, set the foundations of a new archaeological discipline. From the early 1960s one can see interest growing rapidly in the application of natural scientific methods in archaeology and, in particular, to metallography in the Soviet archaeological community. One of the reasons for this was the foundation of the Laboratory of Natural Scientific Methods in the Institute of Archaeology on the initiative of B.A. Kolchin, as well as a series of meetings and conferences devoted to the use of new methods in archaeology. The figure shows a dramatic rise of works on ancient iron-smithing over this period. Interest in the history of the blacksmith's craft continued to grow, and so did the number of publications. The figure shows another increase at the turn of the 1980s/1990s that is even more dramatic. At that time the annual number of publications on archaeological metallography exceeded ten titles, and the year 1989, when more than twenty works were published, was a peak one. It was at that time that a series of doctoral theses on the history of the blacksmith's craft were defended within two or three years. Another factor in this dramatic growth of archaeometallographic publications was the energetic work not only by researchers in the capital cities (Moscow, Kiev, and Minsk), but also by colleagues from peripheral scientific centres (Yekaterinburg, Ulyanovsk, Pskov, Kemerovo). The early 1990s saw the start of a decrease in publications caused by the general crisis in Russia and CIS countries. The number of publications began to rise again at the end of the 1990s, leading to the belief that the decrease in publications had been no more than a temporary phenomenon caused by

external factors and not by a crisis of archaeometallography as a scientific discipline.

Most of the papers and monographs (about 40% of the total) were dedicated to the Slavic and Old Russian blacksmiths' craft. Among them may be singled out such works as *Ferrous metallurgy and metalworking of Old Russia* and *The ironworking craft of Novgorod the Great* by Boris Kolchin, the monograph by the Ukrainian archaeologists on metallurgy and metalwork of the early Slavs and Kievan Russia (Voznesenska *et al.* 1996), and *The blacksmith's craft of the Polotsk land* by M.F. Gurin.

A considerable part of these studies works concerns another important problem of the history of the blacksmith's craft – the origin of ferrous metallurgy and metalworking in Eastern Europe. To a considerable extent these aspects are still the subjects of debate. Nevertheless, thanks to the research by N.N. Terkhova, G.A. Voznesenskaya, L.S. Rozanova, and B.A. Shramko, it can be stated with confidence that Eastern Europe was a secondary zone for the introduction of iron by comparison with Asia Minor and the Caucasus. Whilst the East European tribes had some individual iron tools (made of meteoritic iron) in the second quarter of the 2nd millennium BCE (Shramko *et al.* 1965; Terekhova *et al.* 1997, 35–39), Terekhova justly comments that 'the experiments in meteoritic iron processing were not related to the possibility of obtaining metallurgical iron' (Terekhova *et al.* 1997, 39).

The main principles of archaeometallographic analysis were set out by Boris Kolchin in his monograph *Ferrous metallurgy and metalworking of Old Russia* (Kolchin 1953). Kolchin emphasized that *large-scale* metallographic analysis of a considerable number of tools, weapons, craft implements, utensils, etc. is especially important for historical research. Such approach permits the generalization of single technological characteristics which could form the basis for wider historical and technical conclusions (Kolchin 1953, 11–12). It is significant that Kolchin considered this method as a specific historical research tool from the very beginnings of archaeometallography. That is the main reason why in Russian science the history of the blacksmith's craft has been developed not by specialists in the technology of ironworking but by archaeologists.

In the 1960s–1990s the method of archaeometallography was developed by Kolchin's apprentices and followers. Among the scientists who have made the most considerable contributions to this discipline mention should be made of G.A.Voznesenskaya, N.V.Ryndina, N.N.Terekhova, L.S.Rozanova, B.A.Shramko, M.F.Gurin, and others.

In that period two major trajectories for the study of the blacksmith's craft developed. In his monograph *Ferrous metallurgy and metalworking of Old Russia* Boris Kolchin outlined the investigation of iron products

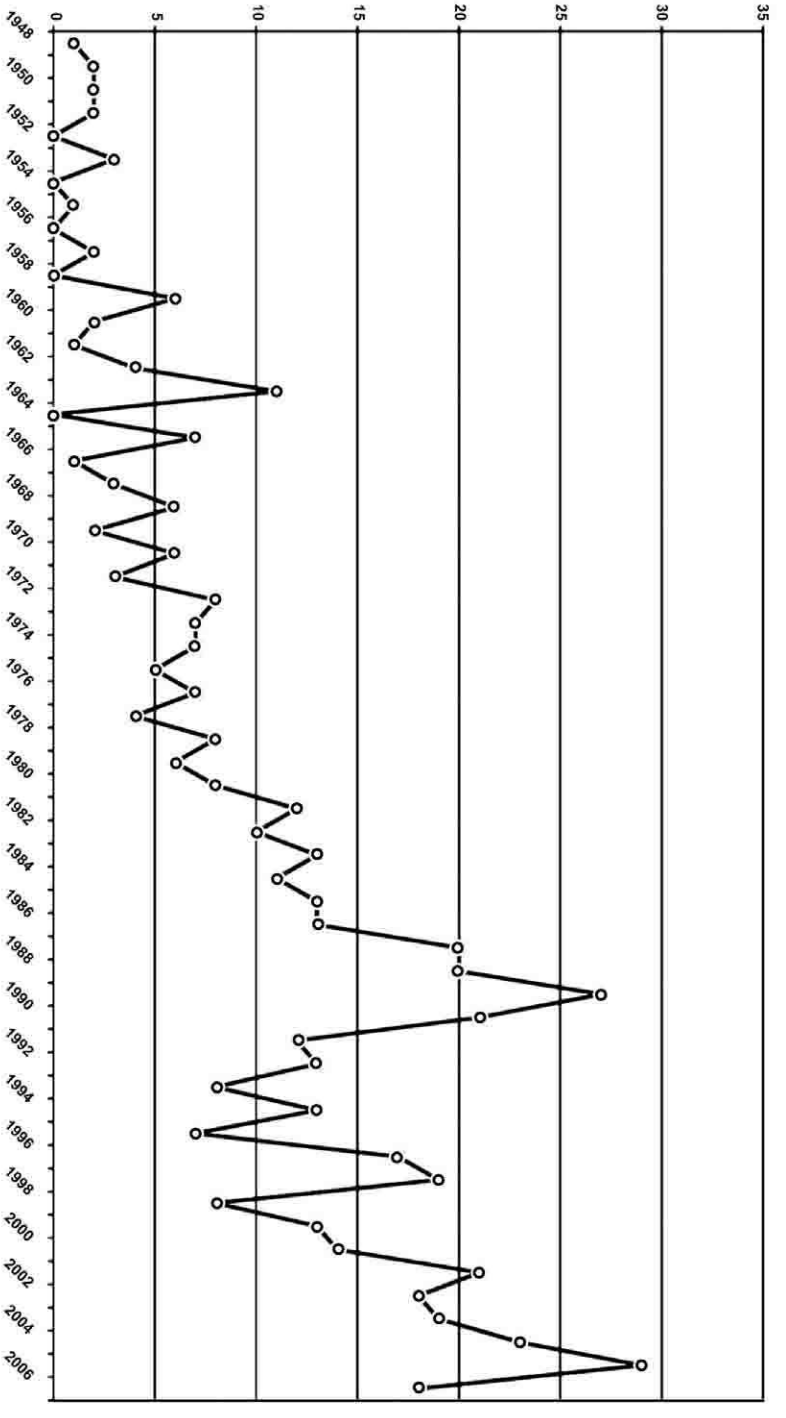

Figure 93: Distribution of archaeometallographic publications in Russia in 1948–2007.

from the Early Iron Age. As part of this research the scientists analysed forged artefacts from sites in the Caucasus and the North Pontic region (Voznesenskaya 1975; Terekhova 1983; 1986; 1989; Terekhova & Erlikh 2000; Shramko 1969; Sramko *et al.* 1965; 1977; 1986) and Finno-Ugrian forged products (Voznesenskaya 1965; Rozanova & Terekhova 2000; 2002; 2002b; 2003; 2003b; Khomutova 1978b; 1982; Zavyalov 2005a). Scientists were also carrying out fruitful studies of the ironworking production of Siberia and the Far East (Len'kov 1974; Zinyakov 1997; Zykov 1986; Zykov & Terekhova 1983; Zykov & Fyodorova 2001; Zhirnykh & Zykov 2001).

The second trajectory was the in-depth study of the craft in certain towns and regions of Old Russia. Here first of all mention must be made of the work by Boris Kolchin *The ironworking craft of Novgorod the Great* (Kolchin 1959), which became a reference work not only for historians of the ancient craft, but also for a broad spectrum of medievalists. The aspects of Novgorod ironworking revealed in this work were later sustained and worked out in detail in the works by L.S. Rozanova and the present author (Zavyalov & Rozanova, 1990; 1992; 2004). The investigation of materials from Kiev (*Novoe v arkheologii Kieva*, 1981), Pskov (Voznesenskaya 1996; Zakurina 1996; 1997; 1998; 2000), Suzdal (Rozanova & Sedova 1984), Chernigov (Voznesenskaya & Kovalenko 1985), Ryazan (Tolmachova 1983; Zavyalov 2004; Zavyalov 2005b), Polotsk (Gurin 1987), Serensk (Khomutova 1973), and Yaropolch Zalessky (Khomutova 1978) have made notable contributions to the history of the Old Russian blacksmith's craft.

The development of Russian archaeometallography, however, did not proceed simply by the quantitative increase of analytical data. The conceptualization of ancient metal and the methods of processing it also developed. Kolchin had pointed to the high microhardness of ferrite from a series of ancient forged products when compared with modern iron, something which he explained as the result of the age-hardening of iron which developed over the course of time (Kolchin 1953, 48). However, in the late 1950s the Polish scientist J. Piaskowski proved the relationship between the microhardness of ferrite and the phosphorus content of the metal (Piaskowski 1959; 1968; 1989). Since then the influence of phosphorus upon the microhardness of ferrite has been confirmed by numerous metallographic surveys of ancient metal objects.

In the Russian scientific literature it was M.F. Gurin alighted upon high-phosphorus iron (Pobal' & Guryn 1975) when studying a series of determinations of the chemical compositions of early iron objects. Later some researchers laid established the main characteristics of phosphoric iron that made it possible to identify this element by means of metallography without carrying out chemical analysis. Among these are the high microhardness of ferrite and its coarse grain structure, a specific structure

of phosphoric liquation, a peculiar silver glance of iron after polishing, and the low etchability of the metal using metallographic agents (Kulakov & Tolmachova, 1987; Nosov & Rozanova, 1989).

The discovery relating to phosphoric iron was made while testing knives made by the three-fold welding process. It was found that phosphoric iron was very often used for the side plates of triple-plated knives (Rozanova & Sedova 1984, 101; Pushkina & Rozanova 1992, 217). A detailed analysis of products made using this technique allowed the researchers to formulate the main characteristics of 'classical three-fold welding technology, among which are a distinct scheme (iron–steel–iron), a specific raw material (high-carbon steel and phosphoric iron), and high-quality welding and heat-treatment of the finished product, usually in the form of hardening by quenching (Zavyalov & Rozanova 1990, 156, 158; Islanova & Rozanova 1994, 232; Terekhova *et al.* 1997, 281).

The comparison of the triple-welding technological scheme and the morphology of knives is of interest. After analysing East European medieval knives R.S.Minasyan has singled out blades with straight backs and accurate ledges at the point where the blade passes into the long tang (the blade to the tang length ratio was 1:2–1:1) as a separate (fourth) group. Minasyan connects the origins of this type to Northern Europe where such knives were common as early as the Merovingian period (Minasyan 1980, 73). It should be noted that Kolchin was the first to justify the relationship between such knives and the technological process of triple welding (Kolchin 1959, 51–52). Further analysis of East European knives led the scientists to prove not only the Scandinavian origin of the 4th group of knives, but also the 'classical' three-fold welding process as the most characteristic of them (Khomutova 1984, 208; Kochkurkina & Rozanova 1987, 90; Zavyalov 1989).

There have been some fundamental changes in the evaluation of the technical and technological structure of the Old Russian blacksmith's craft. As a result of the earliest studies of the products of the Old Russian blacksmiths B.A. Kolchin came to the conclusion that the South and the North of Russia exhibit the same techniques and the same regularity in their use (Kolchin 1953, 184). However, this conclusion had to be corrected as a result of further accumulation of analytical data. In the 1980s G.A. Voznesenskaya and L.S. Rozanova discovered that technological traditions in blacksmith production of Northern and Southern lands of Russia were different (Voznesenskaya & Kovalenko 1985, 107; Voznesenskaya 1990, 83; *Novoe v arkheologii Kieva* 1981, 283; Kochkurkina & Rozanova 1987, 92; Pushkina & Rozanova 1992, 218; Rozanova & Sedova 1984, 103). This observation, the result of many metallographic tests of the products of the Old Russian blacksmith (mainly knives) turned out to be quite effec-

tive. Recent investigations have demonstrated differences in production between the North and the South of Old Russia in other craft branches as well.

The monograph *Essays on the history of ancient iron working in Eastern Europe* (Terekhova *et al.* 1997) represents an important stage in the investigation of the ancient blacksmith's craft. The authors summarize their long-term metallographic research on East European materials. One of the most important results was the identification of the main stages in the history of the blacksmiths' production. The authors outline the stages of ironworking techniques development from the earliest knowledge of native or meteoritic iron and the introduction of metallurgical techniques of iron production through to the High Middle Ages. The researchers report the comparative analysis of the chronological and cultural aspects of ironworking technique and trace the diverse development of the blacksmith's craft in different regions. The conclusions are based on the experimental data, which present standard patterns for every stage of the metallurgical and technological processes (Zavyalov *et al.* 2001, 3).

Long-term archaeometallurgical research has provided archaeologists with a tool that has been tested over time for the study of one of the most important crafts, that of the blacksmith. The development of Russian archaeometallography have demonstrated the achievement of the discipline since it was first outlined by Boris Kolchin. Nowadays it is impossible to study the history of the craft of the blacksmith or even to investigate an archaeological culture or a single site in its entirety without analytical studies.

Acknowledgements

The authors are grateful to the Russian Foundation for Basic Research, which supported this work in the framework of the project No. 11-06-00080-a.

References

Gopak, V.D. 1983, 'Kuznechnye izdeliya pamyatnikov kievskogo tipa v Srednem Podneprovye i Chernigovskom Podesenye', *Drevnerusskoe gosudarstvo i slavyane* (Minsk).

Gurin, M.F. 1982, *Drevnee zhelezo Belorusskogo Podneprovya (I tysacheletie n.e.)* (Minsk).

Gurin, M.F. 1987, *Kuznechnoe remeslo Polockoi zemli* (Minsk).

Islanova, I.V. & Rozanova L.S. 1994, 'Zheleznye izdelia iz pamyatnikov Udomelskogo Poozerya', *Tverskoi arkheologicheski sbornik* 1. (Tver).

Khomutova, L.S. 1973, 'Tekhnika kuznechnogo remesla v drevnerusskom gorode Serenske (vtoraya polovina XII - XIV v.)', *Sovetskaya arkheologia* 2.

Khomutova, L.S. 1978a, 'Rezultaty mikrostrukturnogo issledovaniya kuznechnykh izdeliyi', in M.V. Sedova, *Yaropolch Zalesskiyi* (Moscow).

Khomutova, L.S. 1978b, 'Metalloobrabotka na poseleniyakh dyakovskoyi kyltury', *Sovetskaya arkheologia* 2.

Khomutova, L.S. 1982, 'Tekhnologicheskaya kharakteristika kuznechnykh izdeliyi iz raskopok Tiverska i Paaso', in S.I. Kochkurkina, *Drevnyaya korela* (Leningrad).

Khomutova, L.S. 1984, 'Kuznechnaya tekhnika na zemle drevnei vesi', *Sovetskaya arkheologia* 1.

Kochkurkina, S.I. & Rozanova, L.S. 1987, 'Itogi tekhnologicheskogo izuchenia kuznechnoi produkcii drevnei korely', *Kratkie soobshchenia Instituta arkheologii* 190 (Moscow).

Kolchin, B.A. 1953, *Chornaya metallurgiya i metalloobrabotka v Drevnei Rusi (domongolski period)* (Moscow: Materialy i issledovaniya po arkheologii SSSR No. 32).

Kolchin, B.A. 1959, *Zhelezoobrabatyvayushchee remeslo Novgoroda Velikogo* (Moscow: Materialy i issledovaniya po arkheologii SSSR No. 65).

Kulakov, V.I. & Tolmachova, M.M. 1987, 'Tekhnologia izgotovleniya kopiy prussov', *Kratkie soobshchenia Instituta arkheologii* 190 (Moscow).

Len'kov, V.D. 1974, *Metallurgiya i metalloobrabotka u chzhurchzhenei v XII v.* (Novosibirsk).

Minasyan, R.S. 1980, 'Chetyre gruppy nozhei Vostochnoi Evropy epokhi rannego srednevekovya (k voprosu o poyavlenii slavyanskikh form v lesnoi zone)', in *Arkheologicheskii sbornik Gosudarstvennogo Ermitazha* 21 (Leningrad), 68-74.

Nosov, E.N. & Rozanova, L.S., 1989, 'Tekhnologia obrabotki zheleza na poseleniyakh Priil'menya v IX-X vv.', *Kratkie soobshchenia Instituta arkheologii* 198 (Moscow).

Novoe v arkheologii Kieva, 1981 (Kiev).

Perevoshchikov, S.E. 2002, *Zhelezoobrabatyvayushchee proizvodstvo naseleniya Kamsko-Vyatskogo mezhdurechya v epokhu srednevekovya (tekh-*

nologicheskii aspekt) (Izhevsk).

Piaskowski, J. 1959, 'Metaloznawcze badania wcześnosredniowiecznych wyrobów żelaznych na przykadzie zabytków archeologicznych', *Studia z dziejów górnictwa i hutnictwa* 3, 7-120.

Piaskowski, J. 1968, 'Fosfor w starożytnych i wczesnośredniowiecznych wyrobach żelaznych', in *Sprawozdańa z posiedzeń komisji naukowych oddziały PAN w Krakowie* (Lipec-grudzień).

Piaskowski, J. 1989, 'Phosphorus in Iron Ore and Slag, and in Bloomery Iron', *Archeomaterials* 3 (1), 47-59.

Pobal', L.D. & Guryn, M.F. 1975, 'Zhaleznyye vyraby z Taymanava Bykavskaga rayona', *Vesci AN BSSR* (Minsk: Seryya gramadskikh navuk 2).

Pushkina, T.A. & Rozanova, L.S. 1992, 'Kuzntchnye izdeliya iz Gnyozdova', *Rossiiskaya arkheologiya* 2, 200-219.

Rozanova, L.S. & Sedova, M.V. 1987, 'The Art of Metal Working in the Ancient City of Suzdal', in B.G. Scott & H. Cleere (eds.), *The Crafts of the Blacksmith* (Belfast), 101-104.

Rozanova, L.S. & Terekhova, N.N. 2002b, 'Poyavlenie pervykh zheleznykh izdelii u finno-ugrov srednego Povolzhya i stanovlenie mestnoi metalloobrabotki', in *Suchasni problemy arkheologii* (Kiev).

Rozanova, L.S. & Terekhova, N.N. 2000, 'Kulturnye kontakty azelinskikh plemyon (po dannym arkheologicheskoi metallografii)', in *Nauchnoe nasledie A.P. Smirnova i sovremennye problemy arkheologii Volgo-Kamya* (Moscow).

Rozanova, L.S. & Terekhova, N.N. 2002a, 'Osobennosti tekhnologii izgotovleniya nakonechnikov kopii u volzhskikh Finnov v VIII-VI vv. do n.e.', in *Istoricheskie istoki, opyt vzaimodeistviya i tolerantnosti narodov Priuralya* (Izhevsk).

Rozanova, L.S. & Terekhova, N.N. 2003a, 'Etnokulturnyi factor v stanovlenii zhelezoobrabotki u naseleniya Srednego Povolzhya v anan'inskuyu epokhu', in *Chteniya, posvyashchyonnye 100-letiyu deyatelnosti V.A. Gorodtsova v Gosudarstvennom Istoricheskom muzee* (Moscow).

Rozanova, L.S. & Terekhova, N.N. 2003b, 'Kuznechnye tradicii u pozdneanan'inskogo naseleniya Srednego Prikamya', in *Mezhdunarodnoe (XVI Uralskoe) arkheologicheskoe soveshchanie* (Perm').

Rybakov, B.A. 1948, *Remeslo Drevnei Rusi* (Moscow).

Shramko, B.A. 1969, 'Orudiya skifskoi epokhi dlya obrabotki zheleza', *Sovetskaya arkheologia* 3.

Shramko et al. 1965: Shramko, B.A., Fomin, L.D. & Solntsev, L.A. 1965, 'Pervaya nakhodka izdeliya iz meteoritnogo zheleza v Vostochnoyi Evrope', *Sovetskaya arkheologia* 4.

Shramko et al. 1977: Shramko, B.A., Fomin, L.D. & Solntsev L.A. 1977, 'Nachalnyi etap obrabotki zheleza v Vostochnoi Evrope', *Sovetskaya arkheologia* 1.

Shramko et al. 1986: Shramko, B.A., Solntsev, L.A. & Fomin, L.D. 1986, 'K voprosu o zhelezoobrabatyvayushchem remesle v stepnoi Skifii', *Sovetskaya arkheologia* 2.

Terekhova et al. 1997. Terekhova, N.N., Rozanova, L.S., Zavyalov, V.I. & Tolmachova, M.M. 1997, *Ocherki po istorii drevnei zhelezoobrabotki v Vostochnoyi Evrope* (Moscow).

Terekhova, N.N. & Erlikh, V.R. 2000, 'Drevneyishii chornyi metal na Severo-Zapadnom Kavkaze (k probleme vydeleniya tradiciyi)', in *Skify i Sarmaty v VII-III vv. do n.e.: paleoekologiya, antropologiya i arkheologiya* (Moscow).

Terekhova, N.N. 1983, 'Kuznechnaya tekhnika u plemyon kobanskoi kultury Severnogo Kavkaza v ranneskifskii period', *Sovetskaya arkheologia* 3.

Terekhova, N.N. 1986, 'Tekhnologiya izgotovleniya kuznechnykh izdelii iz mogilnika Sultan-Gora III', *Kratkie soobshchenia Instituta arkheologii* 186 (Moscow).

Terekhova, N.N. 1989, 'Kharakteristika tekhniki kuznechnogo proizvodstva zheleznykh izdelii iz Kelermesskikh kurganov i Kelermesskogo gruntovogo mogilnika v Giaginskom rayone', in *Meoty – predki adygov* (Mayikop).

Tolmachova, M.M. 1983, 'Tekhnologiya kuznechnogo remesla Staroyi Ryazani', in *Sovetskaya arkheologia* 1.

Voznesenska et al. 1996: Voznesenska, G.O., Nedopako, D.P. & Pankov R.P. 1996, *Chorna metalurgiya ta metaloobrobka naselennya skhidnoevropeiskogo lisostepu za dobi rannikh slovyan i Kievskoe Rusi* (Kiev).

Voznesenskaya, G.A. & Kovalenko, V.P. 1985, 'O tekhnike kuznechnogo proizvodstva v gorodakh Chernigovo-Severskoi zemli', in *Zemli Yuzhnoi Rusi v IX-XIII vv.* (Kiev), 95-109.

Voznesenskaya, G.A. 1965, 'Metall Troickogo gorodichsha', in *Arkheologia i estestvennye nauki* (Moscow).

Voznesenskaya, G.A. 1975, 'Tekhnologia proizvodstva zheleznykh predmetov Tliyiskogo mogilnika', in *Ocherki tekhnologii drevnikh proizvodstv* (Moscow).

Voznesenskaya, G.A. 1978, 'Kuznechnoe proizvodstvo u vostochnykh slavyan v tretyeyi chetverti I tysyacheletiya n.e.', in *Drevnyaya Rus' i slavyane* (Moscow).

Voznesenskaya, G.A. 1990, 'Tekhnologiya proizvodstva drevnerusskikh nozhei v pervoi polovine XIII v.', in *Problemy arkheologii Yuzhnoi*

Rusi (Kiev).

Voznesenskaya. G.A. 1996, 'Tekhnologiya izgotovleniya kuznechnykh izdelii v drevnem Pskove', in *Arkheologicheskoe izuchenie Pskova* 3 (Pskov).

Zakurina, T.Yu. 1996, 'Kuznecy srednevekovogo Pskova (XV-XVII vv.)', in *Zemlya Pskovskaya, drevnyaya i sovremennaya* (Pskov).

Zakurina, T.Yu. 1998, 'Zhelezoobrabatyvayushchii kompleks v Srednem gorode Pskova' *Rossiiskaya arkheologia* 3.

Zakurina, T.Yu., 1997, 'Topografiya sledov zhelezodelatelnogo i zhelezoobrabatyvayushchego remesla v Pskove', in *Trudy VI Mezhdunarodnogo kongressa slavyanskoi arkheologii* 2 (Moscow).

Zavyalov V.I. & Rozanova L.S. 2004, 'Kuznechnoe remeslo Novgoroda Velikogo: 50 let issledovanii', in *Novgorodskii arkheologicheskii sbornik* 2 (Velikii Novgorod).

Zavyalov, V.I. & Rozanova, L.S. 1990, 'K voprosu o proizvodstvennoi tekhnologii nozhei v drevnem Novgorode', in *Materialy po arkheologii Novgoroda* 1988 (Moscow).

Zavyalov, V.I. & Rozanova, L.S. 1992, 'Tekhnologicheskaya kharakteristika nozhei Nutnogo raskopa', in P.G. Gaidukov *Slavenskii konec srednevekovogo Novgoroda* (Moscow).

Zavyalov, V.I. 1989, 'Tekhnologicheskie skhemy zheleznykh nozhei Vostochnoi Evropy v X-XIV vv.', in *Estestvennonauchnye metody v arkheologii* (Moscow).

Zavyalov, V.I. 1995, 'The Ironworking of the Permian tribes in the Early Middle Ages', in *La farga catalana en el marc de l'arqueologia siderurgia* (Andorra).

Zavyalov, V.I. 1999, 'Itogi izucheniya zheleznykh izdelii iz Mokinskogo mogilnika', in *Novye issledovaniya po srednevekovoi arkheologii Povolzhya i Priuralya* (Izhevsk–Glazov).

Zavyalov, V.I. 2005a, *Istoriya kuznechnogo remesla perman: arkheometallograficheskoe issledovanie* (Izhevsk).

Zavyalov, V.I. 2005b, 'Blacksmiths' craft of Staraya Ryazan': metallographic investigations of recent years', in *International Symposium "Metallurgy in Southeast Europe from ancient times till the end of 19th century'* (Sofia).

Zavyalov, V.I. et al. 2001: Zavyalov, V.I., Rozanova L.S. & Terekhova, N.N. 2001, 'Arkheometallografiya kak istoricheskii istochnik (itogi izucheniya kuznechnogo remesla v Rossii za 1995–2000 gody)', *Kratkie soobshchenia Instituta arkheologii* 212 (Moscow).

Zhirnykh, E.A. & Zykov, A.P. 2001, 'Tekhnologiya kuznechnogo proizvodstva gorodka Emder', in A.P. Zykov & S.F. Koshkarov, *Drevnii Emder* (Ekaterinburg).

Zinyakov, N.M. 1997, *Chernaya metallurgia i kuznechnoe remeslo Zapadnoi Sibiri* (Kemerovo).

Zykov, A.P. & Fyodorova, N.V. 2001, *Kholmogorski klad. Kollekciya drevnostei III-IV vekov* (Ekaterinburg).

Zykov, A.P. & Terekhova, L.N. 1983, 'Metallograficheskie issledovania zheleznykh izdelii gorodishcha Barsov Gorodok XII-XIII vv.', in *Ispolzovanie metodov estestvennykh i tochnykh nauk pri izuchenii drevnei istorii Zapadnoi Sibiri* (Barnaul).

Zykov, A.P. 1986, 'Metallurgiya i metalloobrabotka na pamyatnikakh Rachevskogo kompleksa', in *Problemy Uralo-Sibirskoi arkheologii* (Sverdlovsk).

Archaeometallography in solving historical and cultural problems

V.I. Zavyalov, L.S. Rozanova and N.N. Terekhova

Archaeometallography holds a prominent place among various methods of studying archaeological artefacts. B.A. Kolchin was the first to use metallographic methods for the study of large series of archaeological artefacts in the late 1940s to early 1950s.

The metallographic group formed by the authors of the present article now works actively in the Institute of Archaeology as a part of the Laboratory of Natural Scientific Methods. We have compiled an extensive archaeometallographic database for different epochs and areas including more than 11,000 analysed samples.

By the end of 1980s the problem of classification, generalization, and conceptualization of considerable heterogeneous data on Eastern Europe ironworking methods and technology starting from the earliest centuries up to the Middle Ages had become important. The work on this problem resulted in the book Essays on the history of ancient iron working in Eastern Europe. *Later the main research trend of the metallographic group became the problem of 'Traditions and innovations in the production of ancient peoples (using the example of the blacksmith's craft)'.*

Special attention was paid to the problem of the development of blacksmith traditions among the Finno-Ugrian peoples of the Volga and the West Ural regions. The history of the development of the Finno-Ugrian blacksmith's craft revealed the phenomenon of early (8th–6th centuries BCE) and the sudden appearance of iron objects with developed shapes in the area of the Middle Volga. In the 9th century the blacksmith's craft of the Volga and the West Ural Finno-Ugrian peoples saw a dramatic leap forward connected with these peoples entering into the trans-European trade system by the Great Volga–Baltic Route.

Another important part of the project is the problem of development of production traditions in the Old Russian blacksmith's craft. The results obtained makes it possible to state that traditions of pre-Mongol times survived in the crafts of the Old Russian smiths in the Golden Horde period.

The materials presented here are the major problems in the history of the craft of the East European blacksmith that could be resolved on the basis of archaeometallographic data not only from the historico-technological point of view, but also in terms of wide-scale historical generalizations.

Archaeometallography - Old Russia - Ancient smith's craft - Finno-Ugrian peoples - Technical and technological stereotype

Archaeometallography holds a prominent place among various methods of studying archaeological artefacts. B.A. Kolchin was the first to use metallographic methods for the study of large series of archaeological artefacts in the late 1940s to early 1950s. Thanks to the methods suggested by B.A. Kolchin, archaeological metal objects became a valid historical source. The implementation of a new natural scientific method into the study of an ancient craft made it possible to answer not only the question of what was produced but also of how it had been produced. The fundamental works by B.A. Kolchin, such as *Ferrous metallurgy and metalwork of Old Russia* and *Ironwork crafts of Novgorod the Great* still retain their key role. His works show that there was a smithing craft with developed iron- working technology and significant branch differentiation in Old Russia. The key part of the Old Russian production was the technology of welding iron with steel. The change of welding technological schemes over time was demonstrated by the example of the Novgorod knives. Thus, in the 10th–11th centuries it was the triple welding structure, which in the 12th–13th centuries was replaced by frontal welding, to be followed by oblique welding in the 14th–15th centuries (Kolchin 1959, 119).

The Laboratory of Natural Scientific Methods in the Institute of Archaeology was founded at the instigation of B.A. Kolchin. He specified the study of materials obtained from the sites of the Early Iron Age and the Early Middle Ages as the priority area in ancient studies of the blacksmith's craft.

The ideas put forward by B.A. Kolchin largely defined research trends in the field of the history of the blacksmith and in general. Among his followers the work of the prominent Czech researcher Radomír Pleiner, which has covered the history of the blacksmith's craft in the Old World from the earliest periods until the High Middle Ages, must be highlighted. His work is especially valuable because he makes extensive use of historical sources alongside analytical data.

In Russia Kolchin's heritage was developed in the works of his students and followers. The metallographic group formed from the authors of the present article now works actively in the Institute of Archaeology as a part of the Laboratory of Natural Scientific Methods. An extensive archaeometallographic database has been compiled for different periods and areas which includes more than 11,000 analysed samples. The distribution by chronological period of the artefacts investigated is presented in Fig. 94.

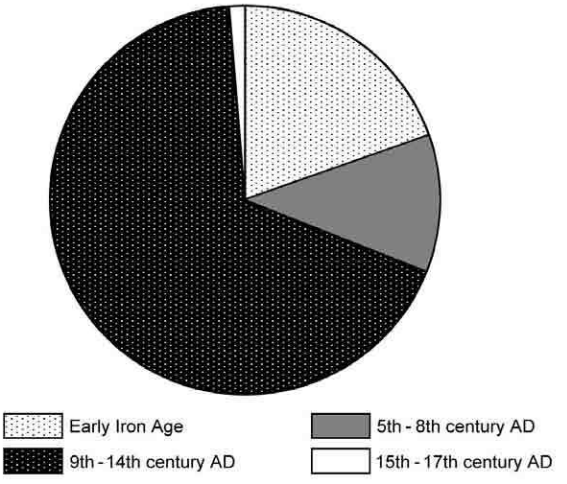

Figure 94: Chronological distribution of metallographically examined blacksmith objects from archaeological sites in the territory of Russia. By V. Zavyalov.

By the end of 1980s the problem of classification, generalization, and conceptualization of considerable heterogeneous data on Eastern Europe ironworking methods and technology starting from the earliest centuries up to the Middle Ages had become important. The work on this problem resulted in the book *Essays on the history of ancient iron working in Eastern Europe* (Terekhova *et al.* 1997).

Later the main research trend of the metallographic group became the problem of 'Traditions and innovations in the production of ancient peoples (using the example of the blacksmith's craft)'. The work on this problem made it possible to show the possibilities of the archaeometallographic method not only for technical and technological problems, but also for historical issues. The work included a realization of a series of interconnected projects (Zavyalov *et al.* 2005).

Recently the group has carried out a cycle of works on various problems relating to the interaction between the barbarian world and the ancient Greek city-states in the sphere of production. A metallographic study of objects from sites of the South-Eastern periphery of the Bosphorus has been carried out. Its objective was to clarify the role of the Bosphoran colonization in the development of local ironworking. Archaeometallographic research showed that the local blacksmiths' traditions were formed in the 5th century BCE. These traditions are characterized by use of simple technological methods and are somewhat conservative. Alien influences, particularly from the ancient world, could not be discerned in local smithing earlier than the 1st century BCE. Changes could not be observed until the turn of the last centuries BCE and the first centuries AD (Malyshev

et al. 1999; Novichikhin *et al.* 2001).

Special attention was paid to the problem of the development of smithing traditions among the Finno-Ugrian peoples of the Volga and West Ural regions. The history of the Finno-Ugrian blacksmith's craft was marked by an early (8th–6th centuries BCE) and sudden appearance of iron objects with developed shapes in the area of the Middle Volga. The analytical results give grounds to conclude that the relationships between the Anan'yino tribes and the Caucasian peoples that could be traced by archaeological materials also covered the sphere of production. The Caucasus smithing traditions did not, however, penetrate the local system of ironworking. The impetus only related to the introduction of iron and the most primitive ways of working it. Finno-Ugrian craftsmen working on base metals adopted the techniques of production and working for iron, but two of the most important technological secrets known by the Caucasian craftsmen – the deliberate production of steel and heat treatment – remained unknown for the local population (Rozanova & Terekhova 2003, 45).

The Finno-Ugrian technical and technological blacksmith stereotype was developed over a long period of time, from the middle of the 1st millennium BCE to the 8th century AD. The stereotype remained unchanged till the 9th century. It could be characterized as follows: a limited range of blacksmith's production, simple technological schemes (the complete domination of artefacts made of solid iron and solid (bloomery) steel)), and occasional use of piled welding structures and technological welding; the main way of heat treatment was quenching, but its use was comparatively rare. It should be emphasized that the Finno-Ugrian technical and technological stereotype is not connected with the initial alien (Caucasian) impetus into the milieu of the Anan'yino people on the Middle Volga in the early 1st millennium BCE.

In the 9th century the craft of the Volga and the West Ural Finno-Ugrian blacksmiths underwent a dramatic leap forward resulting from these peoples entering the trans-European trade system by the Great Volga-Baltic Route (Zavyalov 2005). This resulted in the wide diffusion of blacksmiths' products in general European shapes and the adoption of new technologies by local blacksmiths (Fig. 95). The technical and technological stereotype had changed: the technological welding (triple and welding-in schemes) became the basis of high-quality production, the proportion of heat-treated objects was raised, and the intentional use of a new kind of raw material, phosphoric iron, began. This new stereotype endured thereafter for a long time (until the 15th century).

The craft of the Finno-Ugrian peoples blacksmiths can be described as somewhat conservative. In spite of numerous migrations, the incursion of

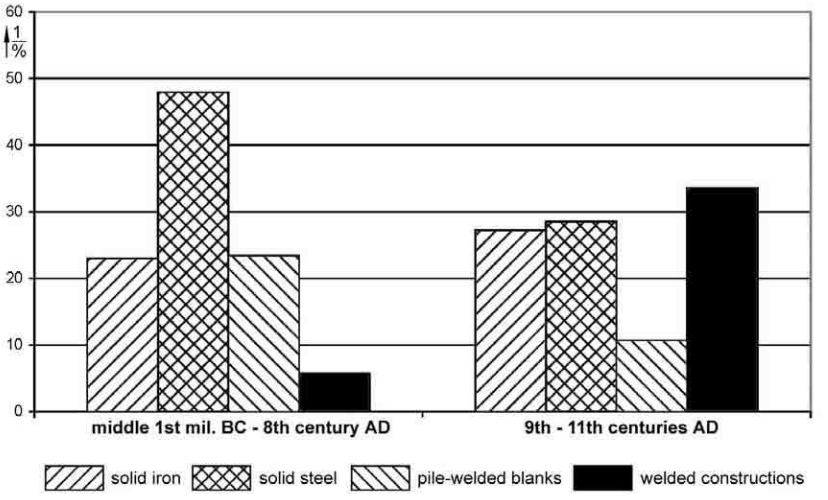

Figure 95: The main technological groups of blacksmiths' production from Finno-Ugrian sites as shown by chronological stages. By V. Zavyalov.

alien peoples into their area, and changes in the local cultures, the stability of their production traditions over long periods of time can clearly be seen.

Another important part of the group's project is the problem of the development of production traditions in the craft of the Old Russian blacksmith. Materials on the craft of the Old Russian smith have greatly increased and as a result it has been possible to correct some of the ideas postulated by B.A. Kolchin. So far as his ideas on general technical and technological models in the territory of Old Russia are concerned, more recent investigations have shown that there were significant differences in production technology in Northern and Southern Russia respectively in the early feudal period (Terekhova. 1997, 265–95). The smithing craft of Southern Russia was based on earlier local traditions, using solid iron and solid steel (Voznesenskaya 1990; 1995). The craft of Northern Russia by contrast is characterized by the predominance of welding technological schemes based on joining a steel blade and an iron base. In the 9th–12th centuries it was triple welding, later replaced by various kinds of welding-on (Fig. 96; Fig. 97). However, triple welding technology had no local roots and was introduced from elsewhere. This technology was developed in the most spectacular way in the work of the blacksmiths of Novgorod the Great (Kolchin 1959; Zavyalov & Rozanova 2004).

The spreading of triple welding structure in Eastern Europe is connected with the development of trans-European trade by the Volga–Baltic route and the foundation of settlements of merchants and craftsmen by multi-ethnic peoples involved mainly in long-distant trade, military campaigns, and craft (Tolochko 1989, 50–59; Nosov 1993, 59–78).

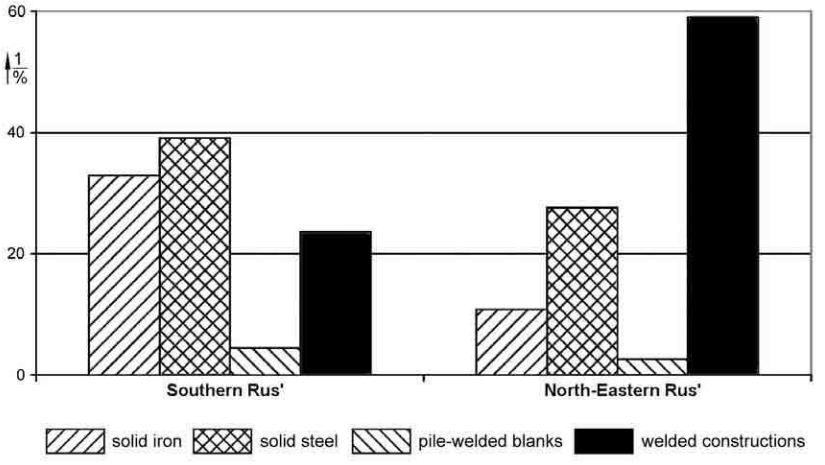

Figure 96: The distribution of technological groups of blacksmiths' objects in Southern and Northern Russia. By V. Zavyalov.

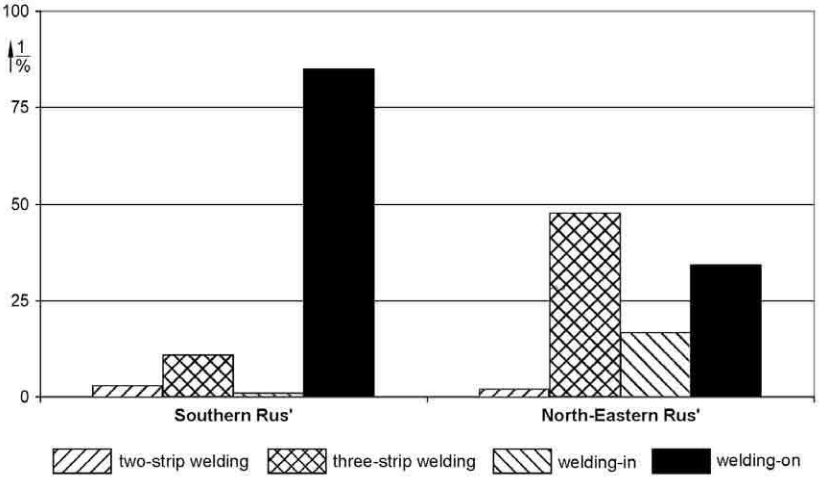

Figure 97: The distribution of welded-on technological production of blacksmiths' objects in Southern and Northern Russia. By V. Zavyalov.

The phenomenon of the spread of the triple welding structure in Eastern Europe is believed to have been related with the Scandinavian factor. Objects made by this technology suddenly appear at precisely those sites where Scandinavian assemblages were found. A characteristic feature of such objects is welding of three plates – two iron and with one steel one between them which comes up to the cutting edge; the iron plates were made of phosphoric iron. The earliest objects made by the triple welding technology in Eastern Europe were discovered in Staraya Ladoga in layers

dated to the second half of the 8th to the early 9th centuries (Rozanova 1994). In Scandinavia proper such goods are known among materials dated to the 7th–8th centuries (Arrhenius 1970; 1989). It is doubtful that the technology of three-fold welding appeared when there was a lack of steel. It is known that in Scandinavia, particularly in Sweden, high-phosphorus iron ores are widespread (Svanidze 1980, 236). On the one hand, this material has a positive quality in that it can easily be welded with high-carbon steel, but on the other hand, the presence of phosphorus hampers the carburization of iron and, therefore, the production of steel.

The technology of welding-on that replaced triple welding in the 12th century, is believed to be related to the Western Slav production tradition (Pleiner 1967). Starting at the end of the 12th century the technology spread widely, and from the 13th century it was the most important welding technological process in the whole of Russia, both Northern and Southern.

The differences between the production spheres of Northern and Southern Russia in the early feudal period are also revealed in the interaction of the urban and rural crafts. Kolchin's view that quality steel and welded objects found in rural settlement were made by specialized urban craftsmen remains true only for Northern Russia.

However, in Southern Russia there was another pattern. Recently G.A. Voznesenskaya of the Institute of Archaeology, the National Academy of Sciences of Ukraine, has carried out a large-scale analytical investigation to identify the technological features of the products made by rural and urban blacksmiths respectively. The research led to the conclusion that objects made by triple welding technology were produced not by urban masters but by craftsmen connected with the estates of boyars and who worked on a single-order basis (Voznesenska 1997; Voznesenskaya 1999, 124).

Voznesenskaya infers that objects made sung the triple welding technique were only like to have been produced by traditional craftsmen who worked in the Scandinavian tradition, not merely triple welding technology but also, and most importantly, the selection of raw materials i.e. the combination of high-carbon steel and phosphoric iron (Terekhova *et al.* 1997).

The Golden Horde period is of great importance in the history of the craft of the Old Russian blacksmith. The controversy about the impact of the Mongol invasion on Old Russian cultural traditions still goes on in the scientific literature. Many researchers believe that the invasion had a disastrous impact on craft activities. According to B.A. Rybakov, "we see the downfall or even a complete disappearance of sophisticated techniques for a series of occupations, crises, and the simplification of crafts in the second

half of the 13th century. After the Mongol conquest a series of techniques known in Kievan Russia vanished; many goods typical for previous epoch ... slate spindle-whorls, carnelian beads, golden glass beads, three-bead temporal rings, granulated beads, and pendant amulets disappear from archaeological finds. The finest cloisonné craft had totally disappeared." (Rybakov 1948, 534).

However, as the archaeological material accumulated, it turned out that the solution of this problem is not so unambiguous. Proceeding from the analysis of various archaeological sources, the researchers came to the conclusion that in many respects there was no break to be seen in the cultural traditions of the peoples of Old Russia. According to N.A. Makarov, "we see a highly more contradictory picture of Old Russia's cultural development where signs of a crisis and a break of succession are combined with the evidence of cultural continuity and the stability of traditions formed in the pre-Mongol period." Archaeological investigations in recent decades have shown that many handicraft products, such as glass bracelets, slate spindle-whorls, *kolt* pendants, and cloisonné objects, were still being produced and used in the second half of the 13th–first half of the 14th centuries (Makarov 2000, 5, 8–9).

So far as the craft of the blacksmith is concerned, the character of its development in the 13th–15th centuries still remains unclear. The group has therefore carried out analytical research of objects from various sites of that period to fill this gap.

The fate of these sites during the Mongol invasion differed considerably. It is known that Novgorod and Pskov, the largest craft centres of Old Russia, escaped the grievous fate of most Russian towns. However, Tartar rule retarded the development of the cultures of Novgorod and Pskov culture. The most obvious evidence of it was the suspension of building in stone until the end of the 13th century (Rybakov 1948, 667). Among the Russian towns that suffered were those of north-eastern Russia, such as (Suzdal, Moscow, Tver, Vladimir, Zvenigorod, etc. However, by the beginning of the 14th century many of them had recovered and continued as urban settlements.

Our research is based on the comparative analysis of metallographic data that characterize the blacksmiths' craft of both the Golden Horde period (13th–15th centuries) and the preceding period (10th–12th centuries). The results demonstrate that the traditions of the pre-Mongol period survived in the Old Russian craft of the Golden Horde period (Zavyalov *et al.* 2007).

The technological process of welding-on dramatically demonstrates the survival of the pre-Mongol traditions in the blacksmith's craft. The technology to be found in single objects as far back as the 10th century played

an important part in the smithing of Old Russia in the 12th century. According to our data, in the following (13th–15th) centuries welding-on was the dominant welding technology (Fig. 98). The process continued both on the sites that escaped the Mongol incursions (Novgorod, Pskov) and on those that had suffered from them (Tver, Moscow).

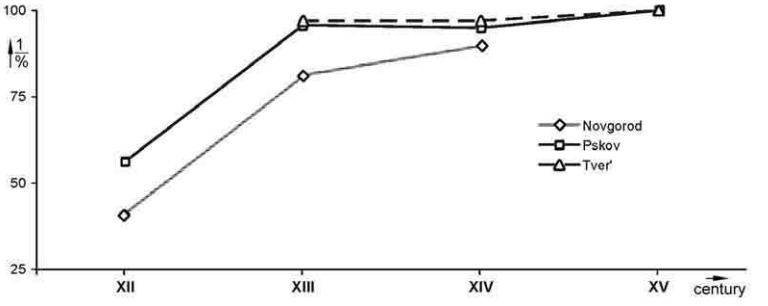

Figure 98: The dynamics of welding-on technology in Old Russian sites of the Golden Horde period. By V. Zavyalov.

The most characteristic examples of the process come from Moscow. In the pre-Mongol time the Moscow blacksmiths' craft developed within the Southern Russian tradition (dominance of solid-metal structures). However, starting in the 14th century objects made by welding-on technology (mainly frontal welding-on) predominate, and the same can be seen in the 15th century. This is believed to be related with the arrival of craftsmen who had mastered welding-on technology. This fact illustrates an historical event, the resettlement of the best artisans and qualified craftsmen in Moscow Principality by the princes in order to strengthen the new political centre (Zavyalov *et al.* 2007, 58).

The complexity and labour-intensive nature of welding-on technology required a knowledge of material properties, the temperature regime of different sorts of ferrous metal welding, various fluxes, the sequence of blacksmith's operations, etc., and this determined the necessity for knowledge transfer from a craftsman to an apprentice, i.e. the institution of apprenticeship. It would naturally be assumed that under the destructive conditions of Tartar rule (demolition of urban infrastructure, capturing of craftsmen, violation of trade contacts, etc.) blacksmith techniques would experience setbacks. However, this cannot been in the archaeological materials. Moreover, the trend in the craft of the Old Russian blacksmiths demonstrated for the pre-Mongol time (increase of number of products made by welding-on technology) continued to evolve. This might be explained by the fact that by the middle of the 13th century welding-on technology had established itself as a stable tradition in the craft of the Old Russian smith. The bearers of this tradition managed not only to

preserve it but also to transfer it to the next generations of craftsmen. In this way the data testify to the fact that there was no break in the blacksmithing traditions, as might have been expected as a result of Mongol invasion.

These are the major problems in the history of the East European blacksmiths' craft that could be resolved on the basis of archaeometallographic data, not only from the historico-technological point of view, but also in terms of broad historical generalizations. The work on the project is in still progress, and in perspective we will face the challenge of filling chronological and geographical gaps.

Acknowledgements

The authors are grateful to the Russian Foundation for Basic Research, which supported this work in the framework of the project No. 08-06-00103-a.

References

Arrhenius, B. 1970, 'Knivar från Helgö och Birka', *Fornvänner: Journal of Swedish Antiquarian Research* 65, 40-51.

Arrhenius, B. 1989, 'Arbeitsmesser aus den Gräbern von Birka', in G. Advisson, *Birka II:3. Systematische Analysen der Gräberfunde* (Stockholm), 79-82.

Kolchin, B.A. 1953, *Chornaya metallurgiya i metalloobrabotka v Drevnei Rusi (domongolski period)* (Moscow: Materialy i issledovaniya po arkheologii SSSR. No. 32).

Kolchin, B.A. 1959, *Zhelezoobrabatyvayushchee remeslo Novgoroda Velikogo* (Moscow: Materialy i issledovaniya po arkheologii SSSR No. 65).

Makarov, N.A. 2000, 'Rus' v XIII v.: kulturnaya situatsiya po arkheologicheskim dannym', in *Rus' v XIII veke: kontuinitet ili razryv traditsiyi?* (Moscow).

Malyshev et al. 1999: Malyshev, A.A., Rozanova L.S. & Terekhova, N.N. 1999, 'Voinskie zakhoroneniya v mogilnike skifskogo vremeni iz Tsemesskoi doliny, in *Istoriko-arkheologicheskiyi almanakh* (Armavir-Moscow).

Nosov, E.N. 1993, 'Problema proiskhozhdeniya pervykh gorodov Severnoi Rusi', in *Drevnosti Severo-Zapada* (Sankt-Peterburg), 59-77.

Novichikhin et al. 2001: Novichikhin, A.M., Rozanova, L.S. & Terekhova, N.N. 2001, 'Tekhnologiya proizvodstva predmetov vooruzheniya iz pamyatnikov VI–IV vv. do n.e. na territorii Sindiki (po materialam Anapskogo arkheologicheskogo muzeya)', in *Istoriko-arkheologicheskiyi almanakh* 7. (Armavir-Moscow).

Pleiner, R. 1967, 'Die Technologie des Schmiedes in der grossm(hrischen Kultur', *Slovenská archeologia* XV (1), 77-188.

Rozanova, L.S. & Terekhova, N.N. 2002, 'K probleme kavkazskikh i mestnykh traditsyi v tekhnologii izgotovleniya zheleznykh izdeliyi iz Starshego Akhmylovskogo mogilnika', *Kratkie soobshchenia Instituta arkheologii* 213 (Moscow).

Rozanova, L.S. & Terekhova, N.N. 2003, 'Etnokulturnyi factor v stanovlenii zhelezoobrabotki u naseleniya Srednego Povolzhya v anan'inskuyu epokhu', in *Chteniya, posvyashchyonnye 100-letiyu deyatelnosti V.A. Gorodtsova v Gosudarstvennom Istoricheskom muzee* (Moscow).

Rybakov, B.A. 1948, *Remeslo Drevnei Rusi* (Moscow).

Svanidze, A.A. 1980, *Srednevekovyi gorod i rynok v Shvetsii XIII-XV vekov* (Moscow)

Terekhova, N.N. et al. 1997. Terekhova, N.N., Rozanova, L.S., Zavyalov, V.I. & Tolmachova, M.M. 1997, *Ocherki po istorii drevnei zhelezoobrabotki v Vostochnoyi Evrope* (Moscow).

Terekhova, N.N. et al. 2006: Terekhova, N.N., Dmitriev, A.V., Malyshev, A.A., Ravich, I.G. & Rozanova, L.S. 2006, 'The foothills of the North-Western Caucasus in 8th–4th centuries B.C.', *Ancient West and East* 5 (1-2).

Tolochko, P.P. 1989, *Drevnerusskiyi feodalnyi gorod* (Kiev).

Voznesens'ka, G.O. 1997, 'Rezultaty analizu zaliznykh vyrobiv sil'skikh poselen' Dneprovs'kogo Livoberezhzhya', in *Pivdennorus'ke selo IX - XIII vv. (Novi pamyatki materialnoi kultury)* (Kiev).

Voznesenskaya ,G.A. 1995, 'O slozhenii proizvodstvennykh traditsiyi v drevnerusskoi metalloobrabotke', *Arkheologiya* 3 (Kiev).

Voznesenskaya, G.A. & Kovalenko, V.P. 1985, 'O tekhnike kuznechnogo proizvodstva v gorodakh Chernigovo-Severskoi zemli', in *Zemli Yuzhnoi Rusi v IX-XIII vv.* (Kiev).

Voznesenskaya, G.A. 1990, 'Tekhnologiya proizvodstva drevnerusskikh nozhei v pervoi polovine XIII v.', in *Problemy arkheologii Yuzhnoi Rusi* (Kiev).

Voznesenskaya, G.A. 1999, 'Tekhnologiya kuznechnogo proizvodstva na yuzhnorusskikh selskikh poseleniyakh'. *Arkheologiya* 2 (Kiev).

Zavyalov et al. 2005: Zavyalov, V.I., Rozanova L.S. & Terekhova, N.N. 2005, 'Arkheometallografiya v izuchenii istorii drevnego kuznechestva', in E.N Chernykh, V.I. Zavyalov (eds.), *Arkheologiya i estestvennonauchnye metody* (Moscow), 92-100.

Zavyalov et al. 2007: Zavyalov, V.I., Rozanova, L.S. & Terekhova, N.N. 2007, *Russkoe kuznechnoe remeslo v zolotoordynskii period i epokhy Moskovskogo gosudarstva* (Moscow).

Zavyalov, V.I. & Rozanova, L.S. 2004, 'Kuznechnoe remeslo Novgoroda Velikogo: 50 let issledovanii', in *Novgorodskii arkheologicheskii sbornik – 2* (Velikii Novgorod).

Zavyalov, V.I. 2005, *Istoriya kuznechnogo remesla perman: arkheometallograficheskoe issledovanie* (Izhevsk).

The multidisciplinary approach (archaeology and archaeometry) to bloomsmithing activities in France: examples of results from the last twenty years

P. Fluzin, S. Bauvais, M. Berranger, G. Pagès and P. Dillmann

Over the last twenty years, archaeological and archaeometrical research implemented in France has made it possible to define the various stages of the chaîne opératoire *in iron and steelmaking (Mangin & Fluzin 2008) as well as the indicators that are linked to them (archaeological structures, wastes). These studies reveal that the* chaîne opératoire *may (or may not) split in space and time, but may also contain varying degrees of intensity (mini-maxi production). This implies that the production sites can be from different natures: they may include partial or complete* chaîne opératoire*, and are part of a social context (e.g., rural, urban, specialized, or domestic craft). The relationships within the* chaîne opératoire *create links between the sites and form a technological, economic, and social network through trade in semi-finished and manufactured products. The evolution of these networks must be studied by taking into account the cultural and political contexts of each period to draw up a coherent understanding of this organization. The determination of site activities (smelting, refining, elaboration, consumption, recycling), as well as intensity, allow a dynamic cartography of these activities, both synchronic and diachronic, to be realized. The physicochemical linkages between the ore, the smelting slag, the post-smelting slag, and the metal produced make possible an eventual understanding of the connection between sites that are part of the same exchange network. This in turn reflects the regional development of metallurgical organization and the trade in iron semi-products and manufactured goods.*

The typological attribution (morphology, level of impurities, iron/carbon composition, phosphorus contents, etc) of semi-products worked on the forging sites also makes it possible to refine the vision of what circulate and of what the sites acquire (Bauvais et al. *in press). Thus, an archaeological and historical study of these data can structure the relative image we have of these relations in the various periods (Mangin* et al.*, 2000a; Mangin* et al. *2000b).*

Bloom - Ferrous semi-products - Slag - Inclusion - Quality

Introduction

Working sequences in the bloomery process, as far as post-reduction is concerned, are more or less numerous and complex. The post-reduction work can begin in continuation of the smelting stage (compacting of the raw bloom) and strive towards final shaping of the artefacts, including the semi-product stage. The *chaîne opératoire* can thus be divided into space and time (Fluzin 2004a; Fluzin *et al.* 2004b) and presents different stages corresponding to several qualitative nuances of the material. Depending on periods and geographical areas, the technical system reflects a global organization that is more or less sophisticated and structured, varying with the context (rural, urban, etc.) and different interactive variables: environmental (raw material resources), social (hierarchy, economy, circulation, exchanges, intensity of production etc.) nature of the production (skills, specialization, etc). (Bauvais & Fluzin 2007; Mangin & Fluzin 2007).

Even though the physico-chemical and thermomechanical characteristics of the material transformation are so far better understood by rigorous crossing analytical methods and observation scales (Mangin *et al.* 2000b; Fluzin *et al.* 2000b), the restoration of the practical reality from archaeology, ethnoarchaeology, and experimentations (Fluzin *et al.* 2001) remains difficult and needs to take numerous methodological precautions.

Thus, to try to decipher and understand not only the activity of a given archaeological site, but also the characteristics of the ferrous materials that circulate, it is necessary at first to proceed to an exhaustive study of the remains (blooms, pieces of bloom, gromps, slag proportion, slag type, cake, shapelessness, lining, semi-products, worked metal fragment, forging scale, rejected fragments, artefacts, tools, etc). These studies must be performed on a significant number of archaeological sites in order to favour the most important corpus (in this case archaeological studies of 600 sites, 105 of them archaeometrically studied, i.e. 700 samples).

Moreover, in view of the heterogeneity caused by the smelting and forging in a solid state, if the morphological criteria can lead to a first typological classification this aspect is not intrinsically a sufficient discriminating factor (particularly for quality distinction). Our work has shown that there is no systematic link between the morphology and internal characteristics of wastes. This observation is true for blooms, semi-finished and manufactured products, and forging slag cakes.

A similarity of shape and aspect is not necessary linked to a similar texture, structure, or chemical composition (Dillmann *et al.* in press). Thus, an exclusively morphological approaches must be considered very carefully because a single artefact can present a substantial internal vari-

ability (composition or inclusion cleanliness gradients for metal, great or lesser degrees of stratifications for slag cakes). For this reason it is necessary to proceed to observation and study of the complete transverse section of artefacts whatever their nature or sizes (Pagès *et al.* 2009).

Our research over twenty years has studied a large number of sites and artefacts covering periods from the Early Iron Age to medieval times. Following the methodology of former work carried out in eastern France (Leroy 1997; Leroy *et al.* 1999; Fluzin *et al.* 2000), in the Swiss Jura (Serneels 1993; Eschenlohr 2001; Eschenlohr *et al.* 2007; Senn-Bischofberger 2005), and as part of several PhD theses (Pagès 2008; Desaulty 2008; Bauvais 2007; Orengo 2003; Berranger 2009), we have significantly completed our multidisciplinary and diachronic investigations on the French territory from the following areas: Nord du Bassin parisien, Narbonnaise (Languedoc-Roussillon, Provence-Alpes-Côte d'Azur), Grande Limagne d'Auvergne, Normandie, Pays de Bray, Pyrénées ariégeoises, and a large part of central Burgundy. More than 600 ironmaking sites and 700 artefacts have been studied.

This work has allowed us to define the internal characteristics of the materials precisely in order to evaluate on the one hand the real nature of the forging activities on given sites, and on the other hand the qualitative criteria that could help to identify some specificities and exchanges.

Reading archaeological wastes: some examples

Following the sequences of the *chaîne opératoire*, several short examples are given. The detailed procedure for metal analysis will not be presented here, since it can be found in the literature (Fluzin 1983; Fluzin 2004a; Fluzin *et al.* 2004).

For the last few years, our team has developed several analytical methodologies to analyse slag inclusions (major element and trace element[4]) embedded in the metallic matrix of the artefacts (in order to discriminate between two processes, direct and indirect: Dillmann *et al.* 2002). With regard to the bloomery process (direct reduction), all the elements that are mainly concentrated in the slag will be present in the slag inclusion of the metallic artefacts, preserving their respective ratios.

To identify inclusions coming from adding made during the forging

[4]Using μXRF analyses under synchrotron radiation, it may be possible in the near future to proceed to trace element analysis of a significant number of inclusions. However, adapted data-treatment programs have to be developed before the routine application of such a technique can be envisaged. A comparative study of all the trace-element analysis methods at the microscopic level has been made as part of the PhD thesis of Stephanie Leroy (2010 – CNRS/Synchrotron SOLEIL/CEA/UTBM).

stage, and also local enrichment effects mainly due to the small sizes of the inclusions, it is necessary to analyse a large number of inclusions for each artefact (at least 40) and then proceed to a filtering of the raw results (Desaulty *et al.* 2009).

Several parameters will influence the mechanical behaviour of ancient ferrous metals. The first one is the carbon content, which changes the hardness, elastic limit, etc. Nevertheless, as far as ancient artefacts are concerned it is necessary to take into account the eventual presence of phosphorus in the metal, but also the slag inclusions and porosities. Finally, it is also important to evaluate whether the artefact is made by welding different metal pieces and to evaluate the quality of the welding lines.

Several studies clearly demonstrate that the presence in the metal of relatively low quantities of phosphorus (more than 0.1%) can drastically change the mechanical behaviour of the metal and consequently its commercial or technical value. It seems, moreover, that specific technical gestures must be used in order to forge and weld it correctly (Vega *et al.* 2003a; Vega *et al.* 2003b), and so it appears that phosphoric iron must be considered as a specific material.

Depending on the smithing stage (cleansing) and on the slag quantity initially present in the raw bloom (but also on the final shape of the artefact), more or fewer slag inclusions remain embedded in the semi-finished and finished products. They have been shown to be a very useful mean of distinguishing smelting processes and provenances. However, as far as the mechanical behaviour of the metal is concerned, they can drastically modify the quality of the metal.

Because of their rarity in archaeological context, studies on raw blooms are not so numerous (Pleiner 2000). Most of the observations in our work (24 blooms morphologically studied including metallographic studies on seventeen blooms or fragment of 2–38kg: Fig. 99: a, b /Plate XXV/) confirm the intrinsic compositional heterogeneity of blooms (numerous slag inclusions and porosities, high variability in carbon distribution, from 0.02% to 0.9% and sometimes producing localized inclusions of cast iron). Cast iron may sometimes be considered to be a waste product, but this assertion is not consistent (Fluzin 1999; Fluzin 2000a; Fluzin 2003). Moreover, some blooms can be very homogeneous (ferritic or low carburised steel), showing an excellent mastery of the smelting stage. This kind of artefact is also easily forgeable (Fluzin 2006). Their presence in open urban areas and *oppida* shows (Berranger & Fluzin 2007) on the one hand that the raw materials (blooms) were exchanged as raw semi-product, probably over small distances (but not only: at the present time we are studying fifty blooms associated with fifty bipyramidal bars from the Byzantine period discovered in a wreck near Haifa), and on the other hand that these

areas concentrated the supply and redistribution of it (Berranger 2009, Berranger & Fluzin, in press).

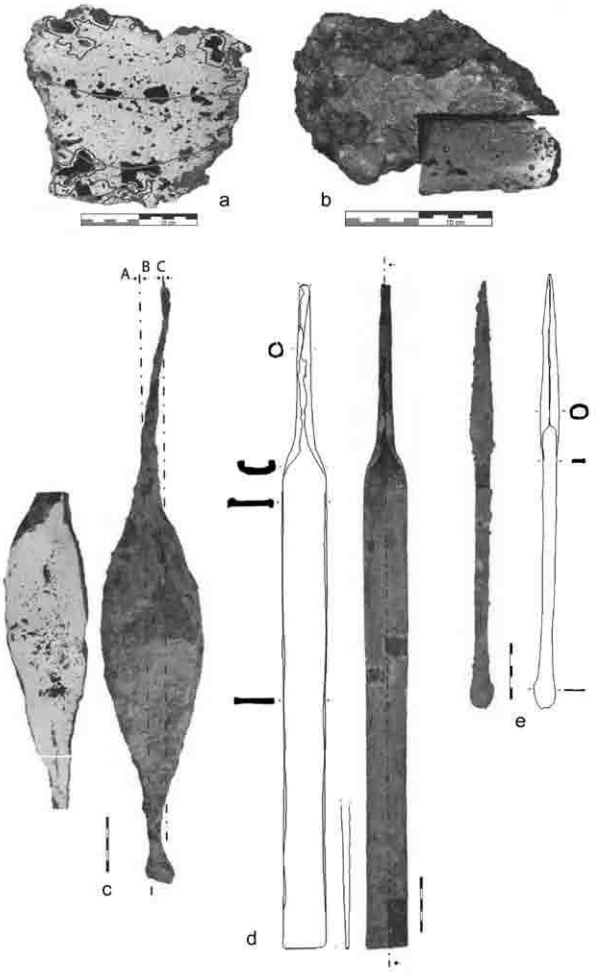

Figure 99: a: Raw bloom from Piani d'Erna (Italy); 2nd century BCE – 1st century AD; weight: 33kg and 38kg (Fluzin 2006); b: bloom from Selongey (Burgundy-France); Gallo-Roman; weight: 2.37kg.; c: iron bipyramidal bar from the hoard of Nottonville (Eure et Loir, France). 8th–5th century. BCE (14C date); NOT.94.14.07; weight 4950g; length 574mm, width 86mm, thickness 78mm.; d: iron 'currency bar' from the Saône river at Pouilly-sur-Saône (Burgundy, France) 3rd–1st century BCE; SAO.81.03.01; weight 650g; length 598mm; width 45mm; thickness 5mm.; e: iron 'socket bar' from the sanctuary of Saint-Maur (Picardie, France), 2nd century BCE; SM.5445; weight 69g; length 387mm; width 22mm; thickness 3mm. Photographs and sketches by P. Fluzin and M. Berranger.

As far as the typology and morphology of semi-products are concerned (Pleiner *et al.* 2004; Pleiner 2006), it appears that in most cases (730 artefacts archaeologically examined including about 200 archaeometric stud-

ies) bipyramidal or salmon-type ingots (80 artefacts analysed) correspond to a bloom or a bloom fragment that has been very summarily compacted (Fig. 99: c /Plate XXV/, Berranger 2009). We also confirm the hypothesis that the more or less strong elongation at their extremity was made in order to demonstrate the forgeability of the metal (qualitative test). In general terms, the thinner the semi product, the higher the cleanness (compacting rate, and forming work).

It is important to mention the exception of the bars from Saintes-Maries-de-la-Mer (Bouches-du-Rhône, France), dated from the 1st century BCE to the 1st century AD. These come from eleven Roman ships, each of which contains 20–150 tonnes of ferrous bars (Pagès *et al.* in press a; Pagès *et al.* in press b; Pagès *et al.* 2008; Pagès 2008, Pagès 2010). Indeed, despite their significant weights (between 1.5 and 33kg) and their cross-sections, which that can be as high as 10.4cm^2, the complete archaeometric study (54 bars) reveals high inclusion cleanness with some technological and morphological standardization. Moreover, the longer bars (1.5m) are made of two to four blooms (or fragments?) welded together by high-quality work (Fig. 100 /Plate XXVI/). These welding lines can be considered to be true technological feats.

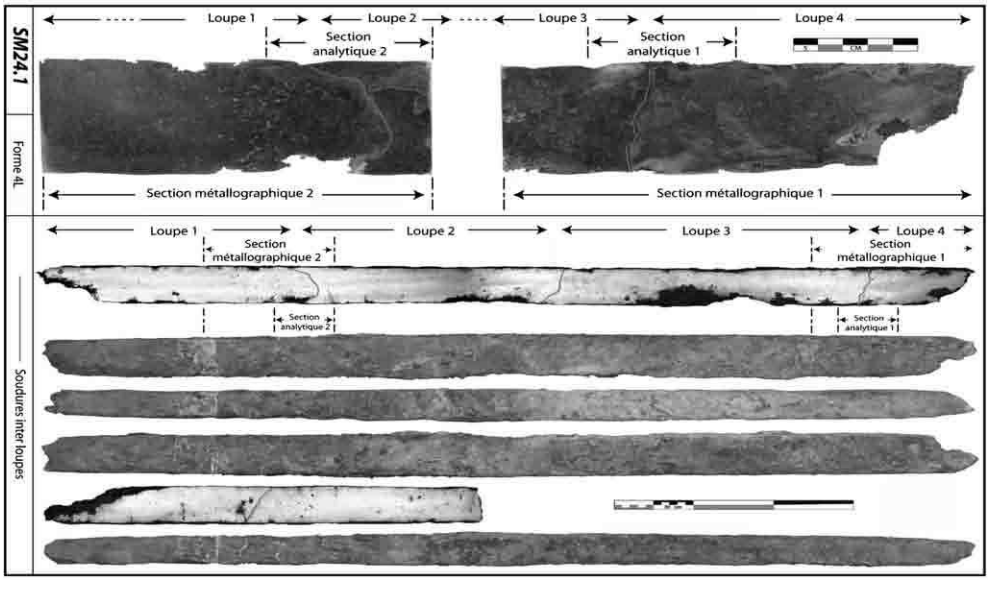

Figure 100: Bars (type 4L) discovered in the Roman wreck (SM24: 1st century BCE to 2nd century AD). Saintes-Maries-de-la-Mer (Bouches-du-Rhône, France). Weight 14kg, length 1160mm, width 58mm, thickness 40mm. Photographs and sketches by G. Pagès.

To sum up these results, metallographic analyses show that the semi-product morphology of the bars correlates with the metal quality. This means that the standard seems to be linked to the metal quality: each

specific morphology is linked to a particular metal. There is no link between this aspect and the ship loading: it can be observed in all the studied ships.

Four groups can be distinguished according to the major chemical element:

1. Blooms with slag inclusions containing high phosphorus levels ($\%_{mass}$ P_20_3 from 8 to 10).
2. Bloom with inclusions with manganese average weighted content ($\%_{mass}$MnO between 2 to 4).
3. Blooms with different $\%_{mass}$MgO/ $\%_{mass}Al_2O_3$ ratios.
4. All the other blooms with no special characteristics.

The fact that some bars are made up of blooms with different major chemical element signatures could indicate that semi-products are not systematically forged on the reduction site as often asserted for this period. They could also be made in different workshops more or less distant from the reduction workshop which import products from different workshops to manufacture the bars (Pagès 2008; Pagès *et al.* in press).

Another form of trade iron are 'currency bars' (Crew 1994). For the most part these exhibit a good to excellent quality of refining (depending on the heterogeneity of the initial bloom), and are made from a single bloom, sometimes hammered by repeated folding (75 objects were examined. Fig. 99: d /Plate XXV/, Berranger 2009).

A new type of semi-product (300 specimens already studied), with the same morphology as the currency bars, but with a lower mass, was also found, 'socket bars' (Fig. 99: e /Plate XXV/). These are small flat iron pieces with a socket (*c* 400 × 20 × 3 mm, average weight *c* 100g). These products seem to be mainly located in the French *Bassin Parisien* during the Iron Age. (Bauvais 2007, Berranger *et al.* 2007, Berranger 2009). Studies have revealed some qualitative particularities – excellent inclusion cleanness; intense hammering by successive folding, which could result in very good mechanical properties; quasi-systematic cementation treatment (probably in order to facilitate welding by lowering the weldability temperature). In the light of these aspects, it appears that these semi-products show specific qualities indicating an elaborated functional role.

Chemical analysis of slag inclusions contained in nineteen socket bars from eight different sites of this sector permitted a more precise understanding of their circulation. The socket bars, which were of local manufacturing and for local use, are composed of metals from various sources. This remark tends to confirm the massive importation of crude iron from distant sectors and local working up (Berranger *et al.* 2007).

The study of forging-slag cakes, and also of irregular slag (perhaps the result of a low-intensity activity that does not produce sufficiently

high quantities to form slag cakes) is also fundamental (Fluzin 2004). Indeed, the forging cake bears witness to what happened inside the forging hearth. It contains all the compounds introduced in the hearth between two cleanings (Mangin *et al.* 2000b).

Our work takes into account more than 360 cakes fully analysed for a total number of about 4000 studied cakes. Their weights vary from 50 to 1000g with an average around 160g; without detailing all the aspects of such a study (Bauvais 2007), some points must be emphasized.

The morphological typology based on external aspects is not representative of the internal composition and can clearly cause erroneous interpretations. Thus, the three main cake families classically used (dense, sandy/clayey, magnetic) can be further divided after studying the complete transverse sections into more than ten categories. This is not surprising when one consider the variety of forging sequences, particularly in the case of polyvalent and versatile activities. Indeed, the precise examination of the outside and the inside of a given cake reveals numerous aspects:

- Dimensions reveal shape and size of the forging hearth and can sometime be correlated with the size of the forged objects. A careful examination often makes it possible to locate the ventilation axis (position of the tuyère).
- On the other hand, the cake weight is not a reliable qualitative criterion and is not representative of the nature of the work. In most cases, the cakes corresponding to cleansing are not heavier than those generated by other sequences.
- The forging cake is very often stratified. It reveals the different working sequences, making it possible to evaluate the nature of the activity, its relative importance and its duration, the intensity, the regularity and the degree of standardisation of the work, the working temperature, the importance of degassing, the degree of oxidation, the nature and the proportion of the material loss, the use of additions, and sometimes the quantities produced. It is then possible to follow in a same cake the work evolution during the forging. For example, the metal loss frequency is higher at the beginning than in the finishing stage.
- The relative evaluation of the metal loss into the cake provides important technical information. The abundance of metallic fragments shows a more or less complex work (forging of an heterogeneous metallic mass, cleansing, welding, work on small artefacts that are difficult to manipulate, etc). Metallographical studies of these fragments makes it possible to distinguish the quality of the material, the intensity of forming, the technical skill of the blacksmith, the

high-temperature oxidation of the metal during forging, the thermochemical treatments (carburization or decarburization).

- The number and the morphology of the oxide scales generated during forging (flat, globular, prills) and the quantity of dissolved iron oxide (wüstite) give an idea of the metal loss by oxidation and the nature of the forging operation (more or less flat product, hammering intensity, welding, etc).
- The presence of sandy/clayey zones, depending on their position in the cake, can reveal the location of the furnace lining or the use of protective additions during the metal heating or of welding. The degree of melting gives an indication of the temperature levels and the duration of the heating sequences. In some cases it is possible to identify more complex additions and mixing of organic and mineral materials, and this can be correlated with specific thermochemical treatments (carbonitriding).
- The absence of metal loss is also important information which can be linked to a regular activity associated with finishing operations.
- The various crystalline phases (fayalite, wüstite, hercynite, etc.) can sometimes give information about oxidation intensity, melting phenomena, temperatures attained, and cooling conditions. In most cases, temperatures are not high enough to cause complete melting of the cake.

This non-exhaustive list illustrates part of the wealth of information that can be gathered from the interiors of forging cakes which can be compared in order to propose hypotheses about the forging operation. An important point is that these hypotheses must also be confirmed by experimental archaeological restitutions. Because of the lack of space, studies concerning gromps, amorphous slag, scraps, etc, will not be described here.

Lastly, all these observations on forging cakes, and also the one made on metallic artefacts detailed here, make it possible to understand more precisely the nature of the activities that were practised on a given site.

Conclusion

This detailed outline and the partial application of the *chaîne opératoire* approaches required to understand the regional organization (Bauvais & Fluzin 2009) of iron and steel making activities show the complexity of such an initiative. Moreover, this complexity lies in each discipline implemented, from engineering science to anthropology.

It is interesting to see that the individual comprehension of these activities is simplified and enlightened when they are approached in a dynamic

and scalable way by confronting them with their context. Three parameters are important to keep in mind:

- The need to possess significant technological analytical tools (via archaeometry) as the basis of any interpretation.
- The requirement for wide knowledge of the socio-economical and socio-political systems underlying these activities, as they are the most crucial and most highly evolving elements.
- The importance of studying a large number of sites in order to be able to transcend the limits inherent to each individual site.

For this type of analysis to be truly fruitful, it is necessary to apply a constant back-and-forth approach between macrographic and micrographic scales, something that is possible with a multidisciplinary methodology.

References

Bauvais, S. & Fluzin, P. (in press), 'Acquisition and circulation of the raw material during the second iron-age in the north of Paris Basin (France)', In P. Crew (ed.), *Early Iron working in Europe II-2007.*

Bauvais, S. & Fluzin, P. 2007, 'Réflexions sur l'organisation technico-sociale des activités de forge à La Tène finale dans l'Aisne', *Revue d'Archéométrie* 30, 25-43.

Bauvais, S. & Fluzin, P. 2009, 'Archaeological and Archeometrical Approaches of the Chaîne Opératoire in Iron and Steelmaking: Methodology for a Regional Evolution Study', in V. Roux, S. Rosen (eds.), *Techniques and People: anthropological perspectives on technology in the archaeology of the proto-historic and early historic periods in the Southern Levant.* Mémoires et Travaux, De Boccard.

Bauvais, S. 2007, 'Evolution de l'organisation des activités de post-réduction dans le nord du bassin-parisien au second âge du Fer': études multidisciplinaires de la chaîne opératoire en métallurgie du fer'. Ph.D. thesis, under the direction of P. Fluzin, University of Technology of Belfort-Montbéliard.

Berranger, M. & Fluzin, P. 2007, 'Organisation de la chaîne opératoire en métallurgie du fer aux IIe-Ier siècle av. J.-C., sur l'oppidum d'Entremont (Aix-en-Provence, Bouches-du-Rhône): la circulation du métal', *Revue d'Archéométrie* 31, 7-22.

Berranger, M. & Fluzin, P. in press, 'Organisation of bloomsmithing activities in agglomeration at the end of the Iron Age (France, II-Ist

c. B.C)', in R. Schwab (ed.), *Symposium on the metallurgy of the European Iron Age*. To be published in Forschungen zur Archäometrie und Altertumswissenschaft.

Berranger, M. et al. 2007: Berranger, M., Bauvais, S. & Fluzin, P. 2007, 'Socket bars: multidisciplinary results (archaeology and archaeometry) on a specific iron semi-product in north of France', in *Proceedings of 2nd International Conference, Archeometallurgy in Europe*, 17-21 June 2007. CD-ROM (Aquileia).

Berranger, M. 2009, 'Le fer entre matière première et moyen d'échange, en France du VII au Ier s. BCE. Approches pluridisciplinaires'. PhD thesis under the direction of P. Brun and P. Fluzin. University of Paris 1.

Crew, P. & Crew, S. 1994, 'Currency bars in Great Britain, typology and function', in M. Mangin (ed.), *La sidérurgie ancienne de l'Est de la France dans son contexte européen. Archéologie et archéométrie*. Annales littéraires de l'Université de Besançon (Paris: Les Belles Lettres), 345-350.

Crew, P. & Crew, S. in press, *Early Ironworking in Europe II. Archaeology, technology and experiment. Second International Conference Plas Tan y Bwlch Sept. 2007* Wales.

Desaulty, A.-M. 2008, 'Apport des analyses chimiques multi technique à la compréhension du comportement des éléments traces dans les filières sidérurgiques anciennes. Application aux études de provenance et à la distinction des procédés', Ph.D. thesis, under the direction of P. Dillmann and P. Fluzin, University of Technology of Belfort-Montbéliard.

Desaulty, A.-M. et al. 2009: Desaulty, A.-M., Mariet, C., Dillmann, P., Joron, J.-L., Gratuze, B., Carlier, C. M.-L. & Fluzin, P. 2009, 'Trace elements behaviour in direct- and indirect-iron metallurgy: the case of Pays de Bray (France)', in *Archaeometallurgy in Europe 2007* (Milan), 318-334.

Dillmann, P. et al., in press: Dillmann, P., Fluzin, P., Desaulty. A-M., Pagès, G., L'heritier, M., Bauvais, S. & Berranger, M. in press, 'An archaeological and archaeometrical approach to ferrous semi-products: typology, quality, origin', in P. Crew (eds.), *Early Iron working in Europe II-2007*.

Dillmann, P., Fluzin, P. & Chevalier, P. 2002. 'Determination of iron-making process using synchrotron microprobe', *British Archaeological Reports International Series*, 1043 (II), 327-334.

Eschenlohr, L. 2001. *Recherches archéologiques sur le district sidérurgique du Jura central suisse* (Lausanne: Cahiers d'Archéologie Romande 88).

Eschenlohr, L. et al. 2007: Eschenlohr, L., Friedli, V., Robert-Charrue

Linder, C. & Senn, M. 2007, *Develier Courtételle, un habitat rural mérovingien 2. Métallurgie du fer et mobilier métallique* (Porrentruy: Cahier d'archéologie jurassienne 14).

Fluzin, P. 1983, 'Notions élémentaires de sidérurgie', in N. Echard (eds.), *Métallurgies africaines. Nouvelles contributions* (Paris: mémoires de la société des africanistes 9), 13-44.

Fluzin, P. 1999. 'Il processo sidérurgico; evoluzione storica e indizi archéometrici. And Ponte di val Gabbia III; i reperti metallici della forgia. Primi resultati dello studio metallografico'. in C. Cucini Tizzoni, M. Tizzoni (eds.), *La miniera perduta. Cinque anni di ricerche archéometallurgiche nel territorio di Bienno.* (Breno), Capitolo VI. 61-92 and Capitolo X, 189-194.

Fluzin, P. 2000, 'Ponte di Val Gabbia III (Bienno). Les premiers résultats des études métallographiques', in C. Cucini Tizzoni & M. Tizzoni (eds.), *Iron in the Alps* (Breno), 24-31.

Fluzin, P. 2003, 'Synthesis of metallographic studies of samples of the site of Ponte di val Gabbia III (Bienno V-VI AD century): obvious facts of pig iron decarburization', in L-C. Norbach (ed.), *Prehistoric and medieval direct iron smelting in Scandinavia and Europe* (Denmark: Acta Jutlandica LXXVI (2), Humanities Series 75), 139-146 and 285-287.

Fluzin, P. 2004. 'The Process Chain in Iron and Steelmaking: Archaeological Materials and Procedures', in H. Bocoum (ed.), *The origins of Iron Metallurgy in Africa* (Paris: UNESCO Publishing, coll. Memory of Peoples), 65-96.

Fluzin, P. 2006, 'Premiers résultats des études métallographiques concernant les masses de métal brutes du site de Piani (IIème Sc. Av J.C.-Ier Sc. Ap JC.)', in M. Tizzoni, C. Cucini, M. Ruffa (eds.), *Alle origini della siderurgia lecchese. Richerche archeometallurgiche ai Piani d'Erna.* (Lecco: Materiali, Monografie periodiche dei Musei Civici di Lecco, Capitolo 8), 129-146.

Fluzin, P. et al. 2000: Fluzin, P., Ploquin, A. & Serneels, V. 2000, 'Archéométrie des déchets de production sidérurgique. Moyens et méthodes d'identification des différents éléments de la chaîne opératoire directe', in C. Domergue, M. Leroy (eds.), *Gallia* 57 (Paris: CNRS éditions), 1-158.

Fluzin, P. et al. 2001: Fluzin, P., Serneels, V., Huysecom, E., Benoit, P. & Kienon H-T. 2001, 'Reconstitution of operating chain in Paleoiron and steel metallurgy from the archaeological remains: comparative studies with the African ethno-archaeology', in S. Beyries, P. Pétrequin (eds.), *Ethno-archaeology and its transfers* (Oxford: BAR International Series 983), 113-122.

Fluzin, P. et al. 2004: Fluzin, P., Ploquin, A. & Dabosi, F. 2004, 'Approches métallurgiques et archéometriques', in M. Mangin (ed.) *Le Fer* (Paris: Editions Errance), 113-174.

Leroy, M. 1997. *La sidérurgie ancienne en Lorraine avant le haut-fourneau. Etude du développement historique et des conditions techniques de l'utilisation du minerai oolithique lorrain (la minette) en métallurgie de réduction directe* (Paris: CNRS éditions).

Leroy, M. et al. 1999: Leroy, M., Merluzzo, P., Fluzin, P., Leclere, D., Aubert M. & Ploquin A. 1999, 'La restitution des savoir-faire pour comprendre un procédé technique: l'apport de l'expérimentation en archéologie du fer', in P. Petrequin, P. Fluzin, J. Thiriot & P. Benoit (eds.), *Arts du feu et productions artisanales* (Antibes: APDCA), 37-51.

Mangin et al. 2000a: Mangin, M., Fluzin, P., Courtadon, J.-L. & Fontaine, M-J. 2000, *Forgerons et paysans des campagnes d'Alésia (Haut-Auxois, Côte-d'Or) Ier siècle avant- VIIIe siècle après J.C.* (Paris: CNRS Edition).

Mangin, M. & Fluzin, P. 2007, 'L'organisation de la production métallurgique dans une ville Gallo-Romaine; le travail du fer à Alésia'. *Revue Archéologique de l'Est* 55,129-150.

Mangin, M. & Fluzin, P. 2008, 'La sidérurgie dans l'est des Gaules de La Tène au Haut Moyen Age. Bilan des recherches et perspectives', in Molin M., eds. *Archéologie et histoire des techniques du monde romain* (Paris: De Boccard), 43-62.

Mangin, M. et al. 2000b: Mangin, M., Courtadon, J-L., Fluzin, P. & De Laclos, E. 2000, *Village, forges et parcellaire aux sources de la Seine: L'agglomération antique de Blessey-Salmaise (Côte-d'Or)*, (Besançon: Annales littéraires de l'Université de Franche-Comté, vol 700).

Orengo, L. 2003, *Forges et forgerons dans les habitats laténiens de la Grande Limagne d'Auvergne: fabrication et consommation de produits manufacturés en fer en Gaule à l'Age du fer* (Montagnac: Editions Monique Mergoil).

Pagès, G. 2008, 'La métallurgie du fer en France méditerranéenne de l'Antiquité au début du Moyen Age: jalons d'une approche interdisciplinaire', Ph.D. thesis, under the direction of P. Fluzin and S. Schmid, University of Montpellier III.

Pagès, G. 2010, *Artisanat et économie du fer en France méditerranéenne de l'Antiquité au début du Moyen Age. Une approche interdisciplinaire* (Montagnac: Editions Monique Mergoil).

Pagès et al. 2008: Pagès, G., Fluzin, P., Long, L. & Dillmann, P. 2008, 'Réseaux de production et standards de commercialisation du fer antique en méditerranée: les demi-produits des épaves romaines des

Saintes-Marie -de-la-Mer (Bouches du Rhône)', *Revue Archéologique de Narbonnaise* 41,33-55.

Pagès et al. 2011a: Pagès, G., Fluzin, P. & Long, L. 2011, 'L'acier, une variété de fer parmi d'autres? Approches méthodologiques des demi-produits des épaves romaines des Saintes-Maries-de-la-Mer (Bouches-du-Rhône, France)', in P. Dillmann, L. Hilaire-Perez, C. Verna (eds.), *L'acier en Europe avant Bessemer, Actes du colloque, Paris 2005* (Toulouse: Méridiennes-FRAMESPA-CNRS).

Pagès et al. 2011b: Pagès, G., Dillmann, P., Fluzin, P. & Long, L. 2011, 'A study of the roman iron bars of Saintes-Maries-de-la-Mer (Bouches du Rhône, France). A proposal for a comprehensive metallographic approach', *Journal of Archaeological Science.*

Pleiner, R. 2000, *Iron in Archaeology. The European Bloomery Smelters* (Praha).

Pleiner, R. 2006, *Iron in Archaeology. Early European Blacksmiths*, (Praha).

Pleiner et al. 2004: Pleiner, R., Fluzin, P., Mangin, M., Vega, E., Dillmann, P., Billon, M. & Rabeisen, E. 2004, 'Lingots et couteaux en fer d'Alésia: études archéométriques', *Revue archéologique de l'Est* 52, 91-130.

Senn-Bischofberger, M. 2005. *Das Schmiedehandwerk im nordalpinen Raum von der Eisenzeit bis ins frühe Mittelalter.* (Leidorf: Rahden/Westf).

Serneels, V. 1993, *Archéométrie des scories de fer. Recherches sur la sidérurgie ancienne en Suisse occidentale* (Lausanne: Cahiers d'Archéologie Romande 61).

Vega, E. et al. 2003a: Vega, E., Dillmann, P. & Fluzin, P. 2003, 'Contribution à l'étude du fer phosphoreux en sidérurgie ancienne', *La revue d'Archéométrie* 26, 197-208.

Vega, E. et al. 2003b: Vega, E., Dillmann, P., L'héritier, M., Fluzin, P., Crew, P. & Benoit, P. 2003, 'Forging of phosphoric iron. An analytical and experimental approach', in *Archaeometallurgy in Europe (Milan)*, 337-346.

Examples of experimental archaeometallurgy

Cast iron from a bloomery furnace
by P. Crew, M. Charlton, P. Dillmann, P. Fluzin, C. Salter and E. Truffaut

The Celtic Sword: a source of practical inspiration
by J. Lang

Cast iron from a bloomery furnace

P. Crew, M. Charlton, P. Dillmann, P. Fluzin, C. Salter and E. Truffaut

A series of experiments have been carried out at Plas Tan y Bwlch smelting high-manganese bog ores as part of a research programme linked to the excavations of the 14th century bloomery at Llwyn Du, North Wales. In experiment 92 the blowing was done with two large hand-bellows, giving a much higher air rate and charcoal burning rate than is usual for a small bloomery furnace. The product was a block of cast iron, which had formed in the normal position of a bloom, held in place by the sticky low-iron slags. This unintended result shows that cast iron in some quantity can be produced relatively easily in a bloomery furnace. There are interesting implications for the increasing number of bloomery sites, from all over Europe, where cast iron and high-carbon steels have been found.

Experiment - Bloomery furnace - Bog ore - Manganese - Cast iron

Introduction

Iron-working experiments have been carried out since 1986 at Plas Tan y Bwlch, the Snowdonia National Park Study Centre in North Wales. Mainly bog iron ores have been smelted in a programme of research linked to the excavations at the prehistoric sites of Bryn y Castell and Crawcwellt (Crew 1991; Crew & Salter 1991, 1993; Crew 1995; Salter & Crew 1997; Serneels & Crew 1997). In 1997 and from 2001 to 2006 excavations were carried out at the 14th century bloomery at Llwyn Du. The iron working there was on a much larger scale than at the prehistoric settlements. Historical records indicate that some 50kg of raw bloom were made each week, refined to some 30kg of bar iron. The smelting was carried out in a large thick-walled furnace with an internal diameter of 40cm, using manganese-rich bog ores and producing tap slags (Smith 1995; Crew & Crew 2001).

As a consequence of these excavations a new series of experiments has been carried out, to explore the problems of smelting with Mn-rich bog ores. In the first experiment (XP90), 20kg of ore was smelted at a blowing

rate of 300 litres per minute, producing a small bloom of 3.3kg, which was fully refined to bar iron. XP91 was a complete failure, mainly because of the poor-quality ore being used. It became clear, however, that a new approach was required to smelt at the rate demanded by the quantification of the medieval process, with the production of tap slag. Thus, in 2004 XP92 was carried out in a modified furnace and blowing at a much higher rate. The result of this experiment, with the production of a large 'bloom' of cast iron, was a surprise. Preliminary reports have been published (Crew 2004; Crew & Charlton 2007) and this more detailed study is presented here as an offering to Radomír Pleiner, both in recognition of his enormous contribution to the study of ancient iron working and in thanks for many years of encouragement and friendship.

Experiment 92: description

The specific aim of this experiment was to use a much higher air rate than the 300 litres per minute that had become normal for our earlier experiments. This was achieved by using two hand-bellows, each of about 30 litres effective capacity, with an overall stroke rate of between 32 and 40 per minute, giving an estimated air rate between 1000 and 1200 litres per minute. By blowing alternately a near-continuous draft could be achieved, with one experienced blower providing a rhythm (Fig. 101 /Plate XXVII/). It was relatively easy to blow for 30 minutes or longer before a rest was required. The air delivery system was set up carefully, with the tapered bellows and long tapered nozzles aligned at the same angle as the blowing hole. The blowing hole area had been modified with a broad splay, to allow the nozzles to reach about half-way through the furnace wall and to give room for rodding the blowing hole when necessary. Tests showed that there was no blow-back and very little entrained air.

The furnace is 400mm in internal diameter, with walls 230mm thick (Fig. 102). This furnace had already been used on a number of occasions and had been adapted to fit the archaeological evidence from Llwyn Du as closely as possible. The furnace had developed a marked curve above the blowing hole, where the wall had melted away. This was re-coated with fresh clay and a sacrificial 'nose' was built to extend the blowing hole for some 50mm into the furnace. This pushes the air flow and the hot zone nearer to the centre of the furnace, in the initial stages of the smelt, until the nose melts. The blowing hole had an internal diameter of 35mm and was inclined downwards at an angle of some 23 degrees.

The charcoal used was commercially made beech, crushed to a size

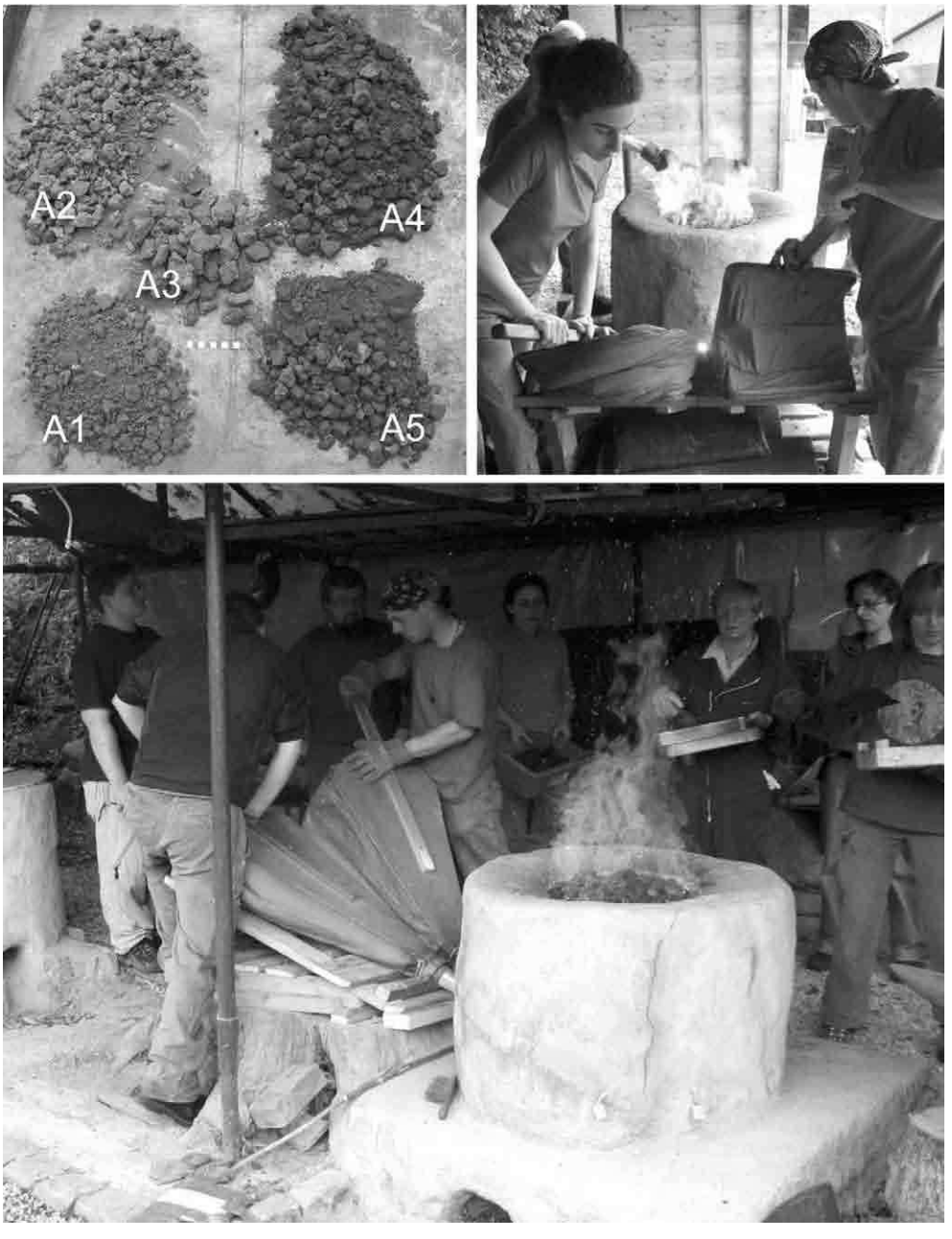

Figure 101: Top left: Batch A bog-ores, scale 10cm. Top right: The bellows and blowing hole. Bottom: General view of the experiment in progress. Photographs by P. Crew

range of 40–10mm, with the finer fraction sieved out. The charcoal burning rate during the main part of the smelt was consistent at a rate of 12–13kg per hour. This is very much faster than in our previous bog ore smelts, but only about half of the charcoal burning rate reported by Sauder &

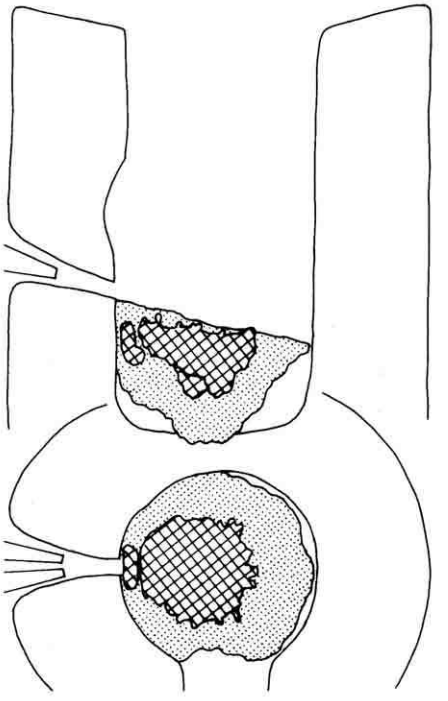

Figure 102: Cross section and plan of the furnace and smelt products; iron cross-hatched, slag stippled. Sketch by P. Crew.

Williams (2002) at an ostensibly similar air rate.

Some 36kg of unroasted bog ore and recycled metal was smelted with 40kg of charcoal in a total time of 5.5 hours. With the fill and post-heat charcoal, a total of 84kg was used, of which about 15kg remained in the furnace at the end of the smelt. Because of the high air rate only a short pre-heat of 30 minutes was needed. The ore was added over a period of 3h and the post-heat lasted for a further 2h.

Thermocouples were set radially at 200mm above the blowing hole level. The recorded wall temperatures rose to over 1000°C and above the blowing hole to over 1300°C. These are much higher than we have recorded before and imply that most of the active zone of the furnace would have been over 1250°C. Extrapolation from more detailed measurements made for previous experiments suggests that there would have been a sizeable volume in the centre of the furnace at an even higher temperature. This is probably near the maximum temperature regime that could be used without causing major damage to the furnace.

No slag was tapped from the furnace. After the last ore was charged the turf blocking of the arch was removed, but there was very little air/flame escaping through the arch. A small quantity of slag (S1) had been fluid

enough to reach the base of the furnace, but had frozen there. It is estimated that around 2kg of the furnace clay was melted and became incorporated into the slags.

The furnace was emptied the following day, revealing a large agglomeration of slag and iron almost filling the furnace below the blowing hole and attached to the front wall of the furnace in the normal position of a bloom (Fig. 102). The top of the slag-iron was at the same angle as the blowing hole, showing that the furnace bed had remained clear with the draft still reaching the rear of the furnace. Although the furnace was very hot it was repaired without too much difficulty and it would have been possible to carry out another smelt immediately (if we had had enough ore and energy!).

Removal of the peripheral slag revealed a core of solid iron, weighing 7.2 kg, roughly in the shape of the mushroom – for convenience the term 'bloom' will be used for this piece in subsequent discussion, but strictly. of course, this is not appropriate (Fig. 103). There was also a small block of iron (920g) in the slag below the blowing hole. It was clear from the smooth cooling surfaces and the high density of the bloom that it had been liquid, or semi-liquid, cast iron. The lower protuberance had clearly flowed into the basal charcoal bed, but had frozen there, suggesting that the temperature gradient below the blowing hole was quite sharp. In addition there were 1.3kg of spheres and small flows of cast iron recovered from amongst the slag and in the base of the furnace, giving a total of 9.4kg of cast iron.

The 8.12kg of the two main lumps of iron is equivalent to a yield of 76% from the estimated iron in the ore. The 1.3kg of loose pieces is roughly equivalent to the 1.5kg of recycled metal from XP90 and 91 added at the end of the smelt, and this is excluded from the yield calculation.

XP92: the ores

One of the primary objectives of this experiment was to smelt with ores as close as possible to those used at Llwyn Du. This was a major difficulty as only 11kg of good-quality ore was recovered from the excavations. The other available ores, from several small deposits on Crawcwellt moor, near to the prehistoric iron-working site, were of poorer quality. The Llwyn Du ores varied from red Fe-rich to black Mn-rich ores, with some of intermediate colour and composition, with the manganese and iron intimately mixed (Fig. 101 /Plate XXVII/). Some of these ores, of course, may have been discarded but analysis of the slags from Llwyn Du shows, without question, that Mn-rich ores were smelted in all three phases (Charlton

Figure 103: The bloom from XP92 after slag removed; top and side views. Scales 25cm. Photograph by P. Crew.

2007). The Crawcwellt ores were similar but had formed in a clay host and so had a higher proportion of gangue. The composition of the ores varied significantly (Table 16). The calculated overall composition of the roasted ore was about 23% SiO_2, 7% Al_2O_3, 12% MnO, and 55% Fe_2O_3, which was not as rich as would have been preferred. The P_2O_5 content was very low for a bog ore, around 0.1%. The SO_3 content was also low, around 0.07%, but this is due to losses in roasting the samples: in the unroasted ore it would have been about 0.3%

Because of this variation in quality, the ores were charged in separate batches, using the good ores first to get the bloom forming, followed by batches of the leaner ores, with the option of stopping the smelt if there were problems with the slag blocking the blowing hole. In the event, the smelt proceeded without difficulty and all the ore batches were smelted. Finally two small charges of very rich ore from Llwyn Du and 1.5kg of recycled metal and metal-rich slag (from XP90 and 91) were added. This method of charging the different ores probably affected the composition of the bloom and this will be discussed below.

A preliminary series of XRF analyses was carried out on small samples of all the available ore types (see Analytical note 1). However, it proved

difficult to make fully homogenized pellets using the unroasted ores and the resulting analyses are not reliable. Nevertheless, these early analyses gave sufficient indication of the relative quality of the ores and six batches were prepared for the smelt. Batch A comprised all the good ores from Llwyn Du and batches B, C, D, and E were the poorer ores from Crawcwellt. These batches were crushed to smelting size (15mm to dust), homogenized as far as possible, and sampled by quartering. At each quartering the ore was crushed to a progressively smaller size to give the final powder samples. These were milled and roasted (LOI between 13% and 17%) and the carefully prepared pellets gave reliable analyses (Table 16).

A final bulk sample was made up of the individual powder samples mixed in the as-smelted proportions. The analysis of this gave a result reasonably close to the mean composition calculated from the dry weights and the individual batch analyses. The discrepancies are a reflection of the inherent variability of the ore and of the difficulty in preparing a fully representative sample.

On the ternary diagram (Fig. 104) an *indication* is given, from the early and unreliable analyses, of the composition of the individual ores from Llwyn Du that were blended to make batch A. This is simply to stress the highly variable MnO in the different ores used.

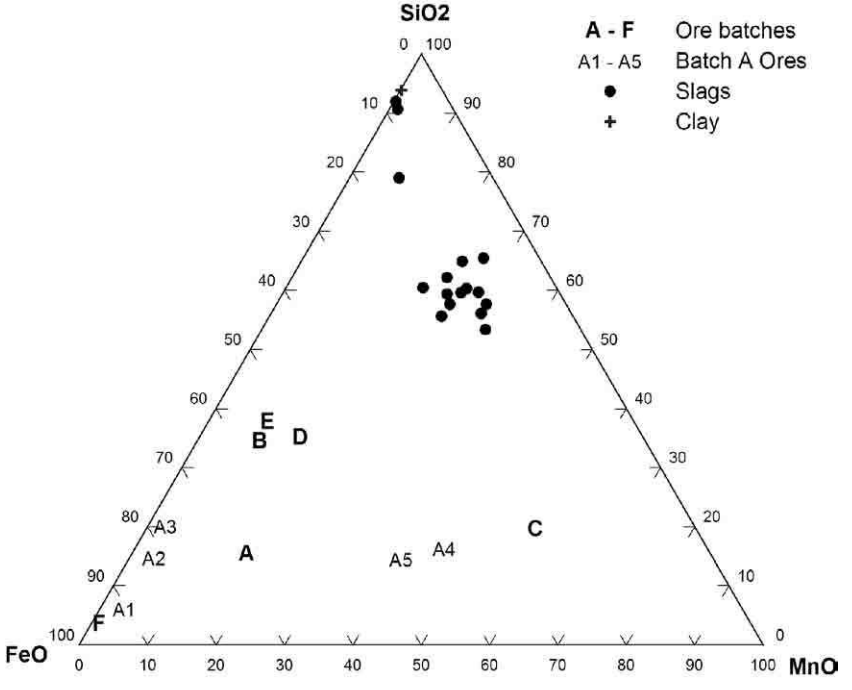

Figure 104: Ternary diagram for the XP92 ores, clay and slags.

Table 16: Ore batches smelted in XP92. The weights are of unroasted ore, as charged. The analyses are of the roasted ores (LOI 13 to 17%), expressed in weight-%, but with the iron returned as Fe_2O_3. Batch A is a mixture of five ores from Llwyn Du. Batches B to E are different ores from Crawcwellt. Batch F was a fine rich roasted ore from Llwyn Du; the unroasted weight equivalent is given. The overall P_2O_5 content is low, about 0.1%.

Ore	*Charges*	*Weight*	*MgO*	Al_2O_3	SiO_2	K_2O	*CaO*	TiO_2	*MnO*	Fe_2O_3
A	9 × 1.2kg	10.8kg	0.06	5.0	13.5	0.64	0.08	0.35	14.3	65.4
B	10 × 1.2kg	12.0kg	0.31	8.8	29.3	1.25	0.12	0.55	7.0	51.6
C	2 × 1.0kg	2.0kg	0.02	7.2	17.5	0.97	0.13	0.49	49.6	22.7
D	4 × 1.2kg	4.8kg	0.13	6.2	30.9	1.08	0.12	0.72	12.4	47.4
E	3 × 1.2kg	3.6kg	0.32	9.1	31.3	1.49	0.12	0.53	7.0	48.9
F	1 × 1.2kg	1.2kg	0.03	0.5	2.7	0.08	1.17	0.03	0.5	94.2
	Total	34.4kg								
A-F	mean		0.24	6.7	22.3	0.96	0.18	0.43	10.0	58.0
A-F	calculated		0.18	6.9	23.1	1.00	0.14	0.47	12.3	54.8

XP92: the slag

The slag, needless to say, is not typical for a normal bloomery smelt. A small quantity of slag had been fluid enough (just) to reach the furnace base, but not to be tapped (S1, S2, S3). These were generally grey in colour, vesicular, and relatively dense. The large quantity of slag attached to the bloom was glassy and rather frothy, some being grey and slightly denser, the majority being light green or pale yellow (S4, S5, S6). Between the bloom and the front wall was a zone of grey dull glassy slag with frequent white inclusions which must have derived from the furnace clay melting (S7). The last flow of slag, lightly attached to the top of the bloom, was dark green and glassy, again with white inclusions (S6T) and would have derived from the furnace wall melting at the very end of the smelt. In total there was some 17kg of slag.

Samples of each slag type, the furnace clay, and fuel ash were analysed by XRF (see Analytical Note 1, Table 17). The slags are remarkable for their low FeO, high SiO_2, and high MnO content and they are well grouped on the ternary diagram (Fig. 104). The early slags S1, S2, and S3 have slightly higher FeO and lower CaO and they probably derived from the richer batch A ore used at the start of the smelt. The S7 and S6T slags are clearly heavily influenced by a large contribution from the furnace wall clay. All of the slags have a relatively high CaO enhancement, about 70 times, clearly due to a significant contribution from the fuel ash (Crew 2007). The SO_3 is remarkably consistent, between 0.3% and 0.4%, showing that much of the sulphur in the unroasted ore passed into the slag.

Perhaps the most remarkable feature of these slags is the consistently high MnO. As the ores had a highly variable MnO content and had been

charged separately in sequence, one might have expected the slag also to have a rather more varied MnO content. There clearly has been some mixing and homogenization of the slags and a possible mechanism for this will be discussed later.

A materials balance is difficult to calculate, as the slag types were so mixed that the weight of each variety analysed could not be measured. Excluding the slag with a strong influence from the furnace clay, the approximate mean slag composition has around 18.4% MnO and 10% FeO. A calculation of an approximate balance suggests that the slags formed from a combination of 91% of ore, 3% clay, and 6% fuel ash. The 3% clay contribution is equivalent to about 1kg, which is about half of that estimated to have been lost; the rest of the clay would have helped form the S6T and S7 slags excluded from the calculation. The calculated yield of iron, from the iron available from the ore, is about 79%. This is rather higher than the measured iron output and suggests that some of the slags would have had a higher FeO content than expressed in the analyses. There is only a slight excess of MnO in the calculated slag, which suggests that little or no Mn remained in the metal.

The S1–S3 slags, which were slightly more fluid, had a higher FeO and lower CaO. It seems likely that these were formed at an early stage of the smelt, thus deriving from the richer ore batch A. A partial materials balance, calculated only from the early slag mean and the batch A ore, gives a high yield of iron (about 90%) and a positive Mn balance, implying that the first 1.5kg of metal could have had an Mn content of about 11%. It seems likely that most of this Mn would have been reoxidized and thus contributed to the later slags, but some of the high Mn metal may have escaped incorporation into the bloom and descended quickly to the furnace base in the form of spheres or small runs of cast iron.

Examination of the B3 cast iron

During the final cleaning of the bloom. part of the lower protuberance, which was only lightly attached, broke off (B3). This provided a convenient piece for examination, which was cut, polished, and photographed before and after etching with 3% nital (see Analytical Note 2; Fig. 105–107). It is clear that this small sample, 7cm long and weighing only some 200g, cannot be regarded as being representative of the whole bloom, but nevertheless its varied structure gives some useful information, which is not easy to interpret. The B3 fragment had been slightly more fluid than the main part of the bloom, running into and cooling in the lower charcoal bed. The lower narrow part had almost separated from the larger upper

Table 17: Slag, clay, and ash analyses from XP92. The data are given for selected oxides only. The clay analysis is of the lute (clay and fine charcoal mixture) used to repair the furnace before the smelt. The charcoal ash analysis is normalized.

Code	*Colour*	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	MnO	FeO
S1	grey	0.87	11.3	40.7	0.29	2.30	6.2	18.5	14.0
S2	grey	0.82	12.5	43.7	0.35	2.50	7.1	19.0	10.5
S3a	yellow	0.99	13.2	43.0	0.29	2.51	7.7	14.2	13.8
S3b	grey	0.87	11.8	41.9	0.30	2.41	6.5	18.4	12.3
S4a	yellow	0.94	11.7	37.6	0.29	1.97	10.3	23.0	9.8
S4b	grey	1.52	10.2	42.1	0.32	1.61	18.6	15.3	7.5
S5a	yellow	0.86	12.6	43.4	0.31	2.35	6.4	17.6	12.0
S5b	grey	0.86	12.5	43.2	0.38	2.67	8.5	15.7	10.5
S5c	grey	1.30	10.6	38.4	0.34	1.82	15.0	20.4	7.7
S6Ba	yellow	1.23	11.6	39.9	0.33	1.88	14.4	19.1	7.9
S6Bb	grey	1.08	11.5	37.9	0.33	1.92	12.6	20.8	8.9
S6Sa	grey	0.72	13.2	43.9	0.31	2.65	6.5	19.3	9.6
S6Sb	grey	1.11	12.8	44.9	0.38	3.00	9.6	18.1	5.6
S6T	green	1.39	10.8	68.3	0.04	3.39	6.3	1.0	6.1
S7a	grey	1.62	12.8	68.4	0.04	2.77	3.2	0.2	5.7
S7b	grey	1.14	11.7	59.9	0.11	3.07	3.6	5.5	10.4
Clay		1.42	10.2	50.9	0.26	2.05	10.8	0.1	3.2
Ash		2.03	0.00	3.8	0.00	11.41	81.9	0.04	0.3

part, leaving a long thin neck of slag, indicating the direction of flow (Fig. 105 /Plate XXVIII/).

The metal had only a few very small inclusions (20μm), all in the grey cast iron, which were devoid of globules and dendrites of wüstite and seemed to be siliceous. There are more numerous voids, of two types. Some are of irregular shape (1– 3 mm), probably from charcoal fragments which had burnt out, and some of regular ovoid shape (200μm to 1mm), probably gas bubbles in locally hot zones.

The metal has a heterogeneous structure, with both grey and white cast iron occurring in discrete areas and in almost equal proportions (Fig. 105 /Plate XXVIII/). The grey cast iron is primarily around the edges of the sample, with the white cast iron as islands within the grey cast iron matrix. The grey cast iron has graphite flakes that are relatively dense, long, and thick (Fig. 106 /Plate XXIX/), corresponding to a hypereutectic structure (>4.3% C). This is corroborated by localized patches of smaller secondary graphite flakes (Fig. 106: E /Plate XXIX/). Some of the flakes in the eutectic structure are gently curved, owing to their derivation from austenite, and there is locally a tendency to radial crystallization, which often precedes the formation of graphite rosettes. This is characteristic of rapid cooling and is usually observed on the surface. In the majority of cases the matrix of the grey cast iron is pearlitic (Fig. 106: B, C, D /Plate

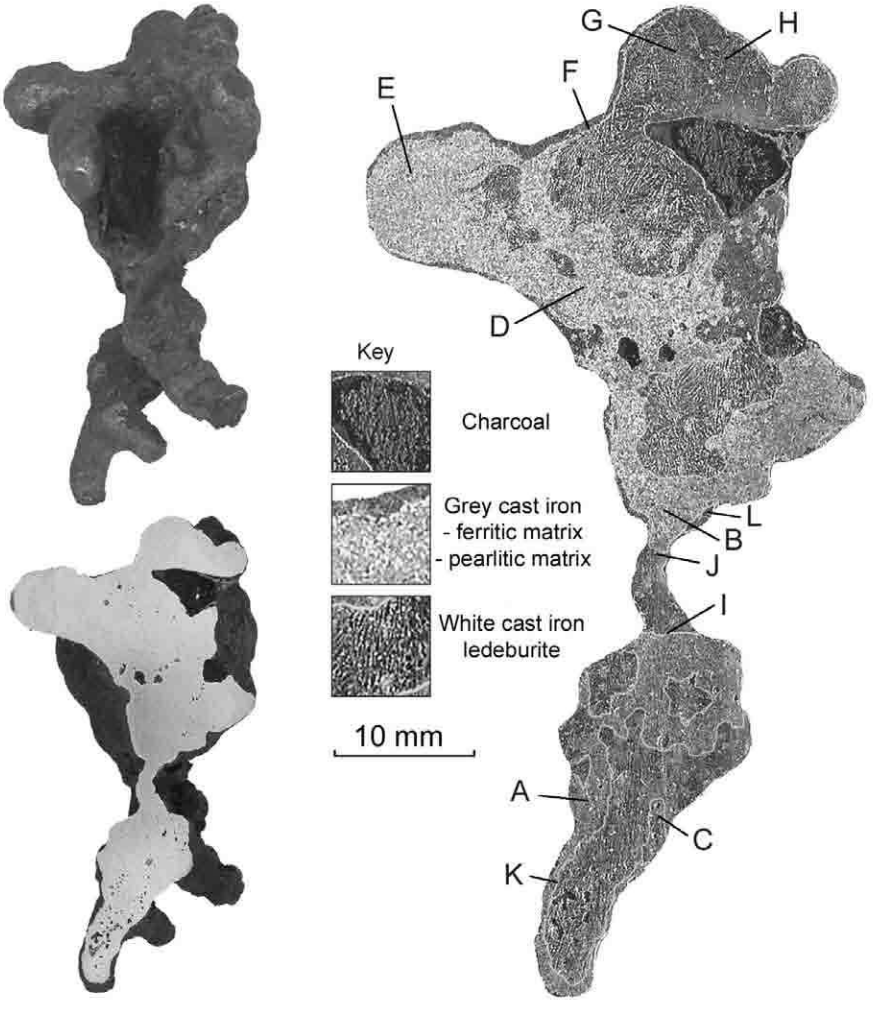

Figure 105: Left: sample B3, cut and polished (approx. 1:1). Right: Macrophotograph of etched sample, with locations of microphotographs A-L (approx. 1:2). Photographs by P. Fluzin.

XXIX/), except around the very edge of the largest part of the sample where the matrix is ferritic (Fig. 106: F /Plate XXIX/), suggesting very slow cooling, perhaps influenced by the thermal inertia of the main bloom.

The white cast iron is characterized by a classic ledeburite structure which indicates a composition close to the eutectic (Fig. 107: G, H /Plate XXX/). Locally the carbon content varies, with rare cases of hypoeutectic structure (<4.3%C). There is a continuous zone of white cast iron surrounding the two charcoal pieces in the larger part of the sample. This reaches almost to the edge of the sample, where it is covered by the thin zone of grey cast iron in a ferritic matrix. The central neck is all white

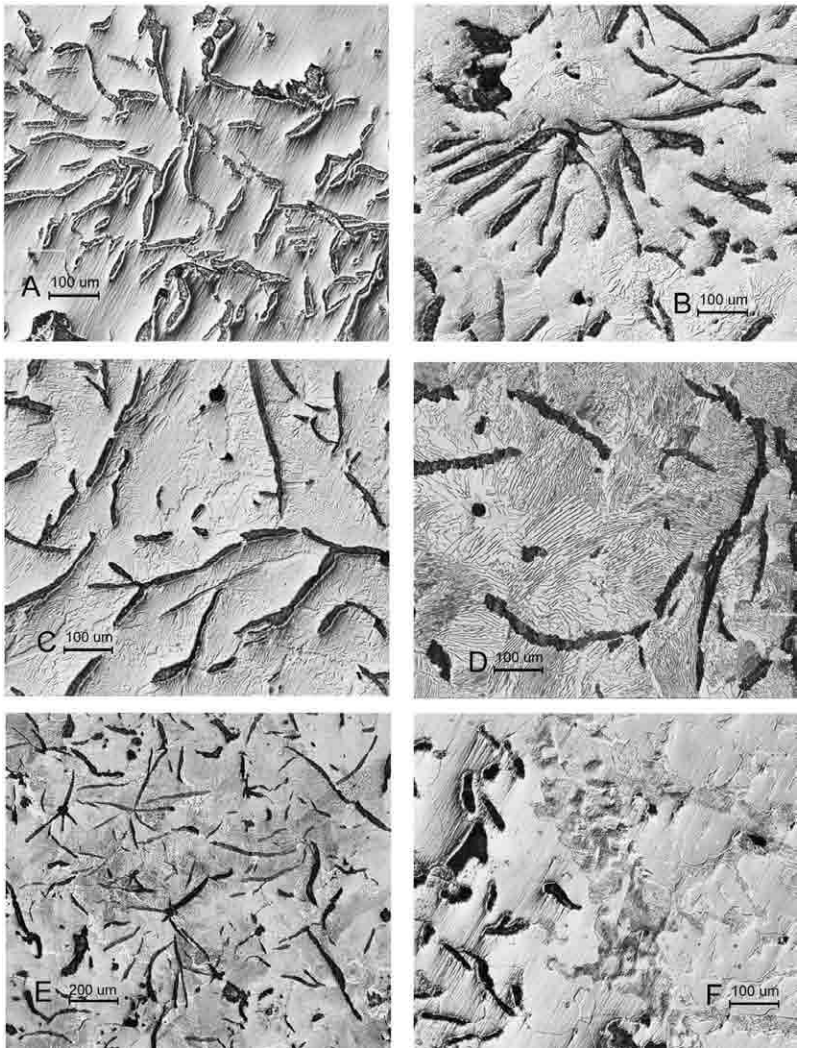

Figure 106: Microphotographs of B3 grey cast iron. Photographs by P. Fluzin.

cast iron, indicating faster cooling in this area.

The transition between the two types of iron is very sharp, with little sign of a mixed structure of grey/white mottled cast iron. This is rather surprising and could indicate a sharp temperature gradient during cooling. On either side of the central neck there is a transition from white to grey cast iron, which has noticeably more irregular graphite (Fig. 107: I, J /Plate XXX/). The direction of the carbide needles in the white iron zone shows the thermal gradient and reveals the direction of cooling. Close to this is a thin zone of ledeburite on the outer edge of the grey cast iron (Fig. 107: L /Plate XXX/), indicating rapid cooling. Around the thin lower part of the sample there is a 600μm zone of grey cast iron around the ledeburite

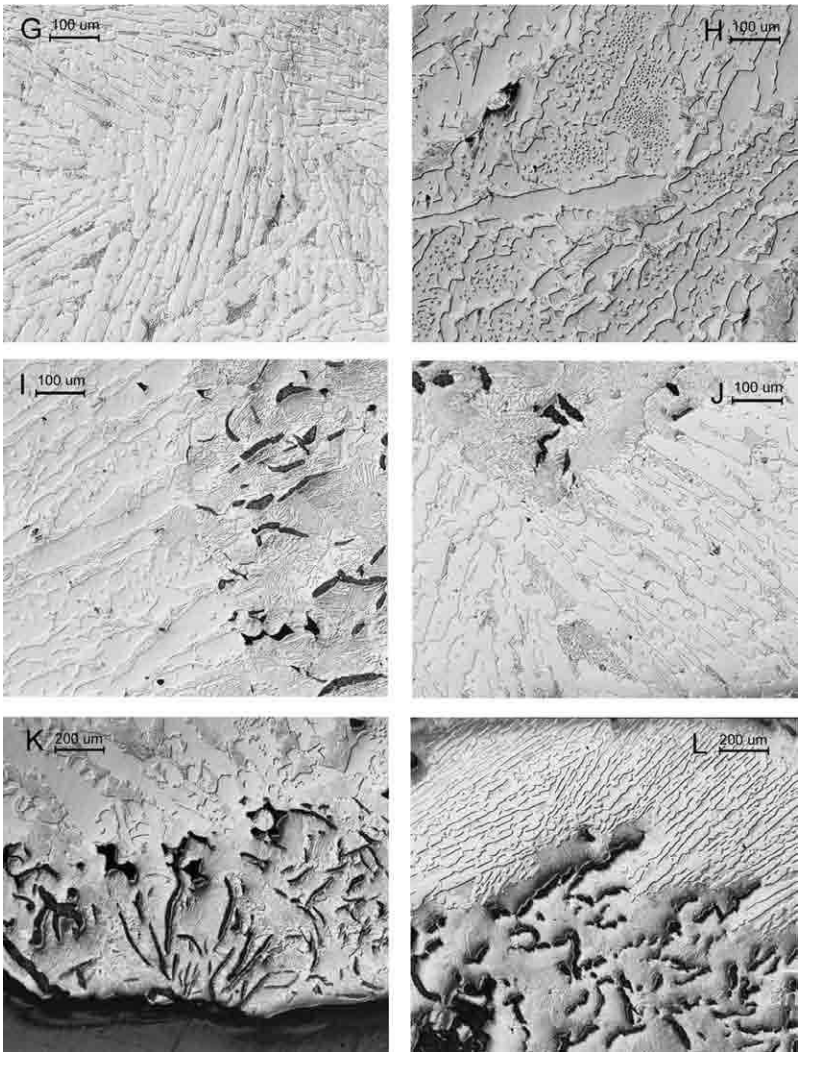

Figure 107: Microphotographs of B3 white cast iron and transitional zones. Photographs by P. Fluzin.

(Fig. 107: K /Plate XXX/), which should indicate a slower cooling of this part of the sample.

There are several factors that can influence the formation of grey or white cast iron. From a strictly thermal point of view grey cast iron is favoured by slow cooling, allowing the formation of the graphite flakes, whereas more rapid cooling favours the formation of white cast iron. It is clear from the description above that cooling rates alone cannot explain all the structures observed. The presence of several elements can also have a strong influence: Si, Al, P, Ni, and Cu are all graphitizing elements, favouring the formation of grey cast iron, whilst Mn, Cr, Mo, and V are

cementizing elements, favouring the production of white cast iron. There is, therefore, a degree of 'competition' between the cooling rates and the influence of these elements. The wide variation of the ores used, and the way in which they were charged, may have had a strong influence, with those richer in Si and Al favouring grey cast iron and those rich in Mn favouring white cast iron. This is illustrated by the examination of two small pieces of iron (S51, S52), one of which was of grey cast iron and the other of white cast iron. These had fallen to the base of the furnace and so presumably would have cooled in similar circumstances.

The interpretation of modern cast irons is relatively easy, owing to the more homogeneous conditions in which they formed, but in the case of XP92 the mixture of structures, all around the eutectic, is particularly difficult to interpret. This is undoubtedly due a combination of factors, both because of the mixture of ore types used and the variable temperature and cooling conditions in the bloomery furnace. In contrast, the main bloom would have been held at a high temperature for a long period, which should have resulted in a more homogenous structure, probably being predominantly grey cast iron. This seems to be confirmed by the examination of a small flow from the base of the bloom (B22) which is also entirely grey cast iron but still retaining a few small areas of white cast iron.

Analysis of the B3 metal

SEM-EDS analysis was carried out on both the grey and white cast iron (Analytical Note 3). The analytical windows were chosen carefully to be as large as possible, whilst avoiding slag inclusions and precipitates. Silicon was detected at about 2% in some of the grey cast iron, which is in good agreement with the presence of graphite flakes, but depending on the location within the grey cast iron, the silicon content could be lower. In the white cast iron no significant quantities of elements other than iron were detected. In both the grey and white cast iron, the Mn is not present in the metal in significant quantity; Mn was also searched for in the carbide (cementite needles in the white cast iron) but was not found.

In both the grey and the white cast iron there were small precipitates of MnS with an angular form, characteristic of formation in a liquid bath of metal. Their average size is 10μm (Fig. 108). There were small globular slag inclusions only in the grey cast iron. One example has O 18%, Mg <0.5%, Al 4%, Si 13.5%, P <0.5%, S <0.5%, K 0.8%, Ca 11.6%, Ti 1.2%, V <0.5%, Cr <0.5%, Mn 1.9%, and Fe 49%. The Si/Al ratio is similar to that of the mean ore, whereas the Mn is considerably lower than in the

Table 18: SEM-EDS analyses of the B3 sample.

Weight−	*Grey*	*White*
Si	1.9	< 0.5
P	< 0.5	< 0.5
S	< 0.5	< 0.5
Mn	< 0.2	< 0.2
Fe	98	99

ore.

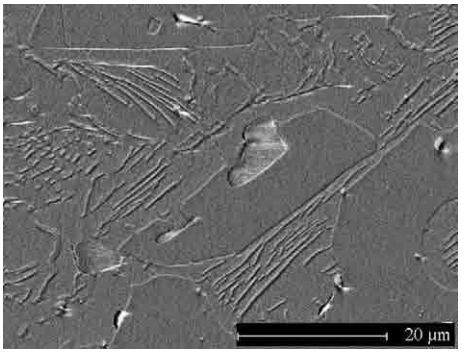

Figure 108: MnS precipitates in B3. Photograph by P. Dillmann.

From these observations it seems that Mn is not present in the metal in a significant quantity and thus cannot be invoked to explain the different cast iron structures. However, the presence of the precipitates implies that a small amount of Mn was reduced and, because of its strong affinity for sulphur, it would have combined with the small amount available to form the MnS precipitates.

The presence of Si in the grey cast iron and not in the white could partly explain the structural difference. However, Si is not always present in the grey cast iron and so it can not be the only parameter to be considered, and the local cooling rate may have been one influence.

Analysis of the S51 and S52 metal

SEM-EDX analysis was carried out on these two small flows of iron, which were recovered from the base of the furnace (Analytical Note 4, Table 19, Fig. 109). S51 is all grey cast iron with a carbon content near the eutectic (Fig. 109: A). There are small areas within the metal that have some iron phosphide, which also occurs along grain boundaries. In the low P areas the Mn content is about 0.26% and general analyses along

Table 19: SEM-EDX analyses of the S51 and S52 samples. All elements analysed, data normalized and expressed in weight-%. General area carbon is not included as the sample was carbon-coated. The value for Fe in the linear MnS inclusion is too high because of the background effects.

	Sample area	*Size, μm*	*Al*	*Si*	*P*	*S*	*Mn*	*Fe*
S51	high P area	50×30			7.55	0.29		92.2
	low P area	130×100					0.26	99.7
	general traverse	800	0.17		0.36	0.13	0.12	99.2
	general traverse	1000	0.05	0.02	0.97	0.02	0.14	98.8
	MnS inclusion	10×5				36.0	55.7	8.3
	MnS inclusion	4×3				33.3	54.0	12.7
	MnS inclusion	10×6		0.08		35.5	56.3	8.2
S52	general area	600×600		0.01	0.58	0.09	0.47	98.9
	general area	600×600	0.05	0.09	0.44	0.17	0.33	98.9
	MnS inclusion	3×3				29.3	47.3	23.4
	linear MnS incl.	12×1	0.10	0.05	0.18	21.0	36.0	46.7
	MnS inclusion	6×3				35.4	61.7	2.8

linear traverses have a lower Mn at 0.1–0.14% and Si at only 0.02%. There are MnS inclusions up to 10μm in size, some of which have fringes where graphite has nucleated but not grown into flakes (Fig. 109: B). The most notable feature of this grey cast iron is that it has virtually no silicon.

S52 is essentially a white cast iron, with a few areas which may be an Fe–Fe_3C–Fe_3P eutectic. It has a complex structure with a central zone of Widmanstätten carbide separated by areas showing a eutectic (ledeburite) type structure, but with the austenite now in the form of ferrite rather than pearlite. Towards the edge of the sample there is a narrow zone with a ferritic matrix and, at the edge, the metal begins to be recarburized to pearlite (Fig. 109: C). The central zone has incipient graphite formation (Fig. 109: D). Two area analyses in the central zone have Mn between 0.33% and 0.47% and with relatively low S, implying that not all the manganese is in the form of the sulphide. There are numerous small MnS inclusions, with a variety of morphologies, all constrained by the Fe_3C in the inter-lath spaces (Fig. 109: E).

The difference between these two samples, which both must have cooled relatively quickly, is probably due mainly to the Mn content, with about 0.1% in the grey cast iron and up to 0.5% in the white cast iron.

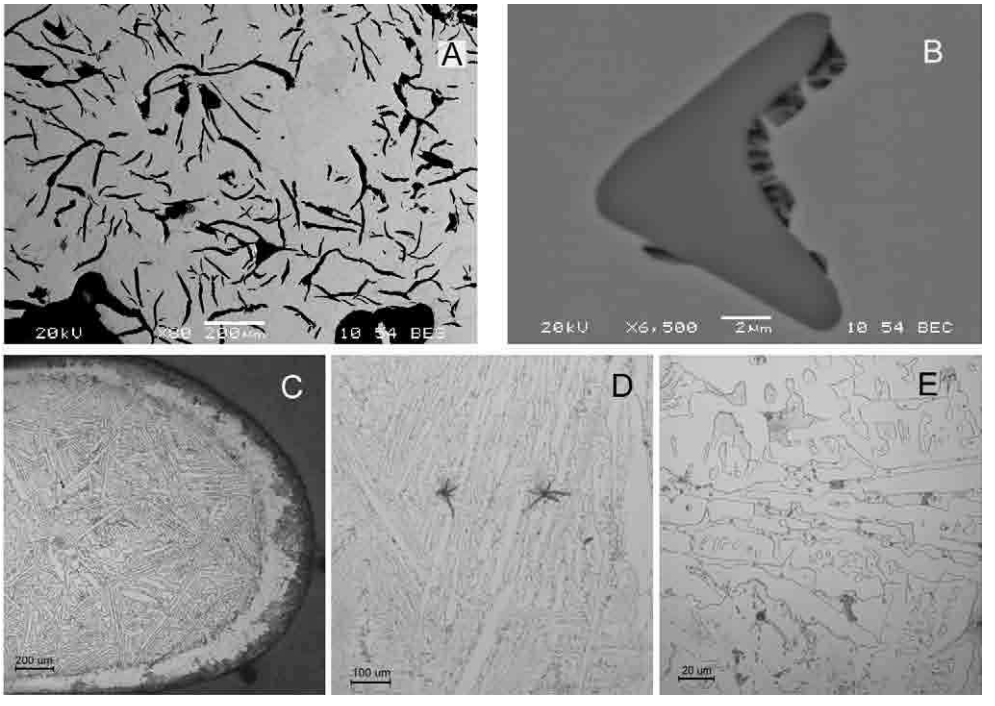

Figure 109: S51 BSE images: A grey cast iron, B MnS inclusion. S52 images, etched 2% Nital: C white cast iron with ferritic fringe, D central area with incipient graphite, E MnS inclusions. Photographs by C. Salter.

Discussion

From the point of view of bloomery iron production this experiment was a failure. The results, however, are of some interest as they effectively represent what is possible at one extreme of the conditions that can be achieved in a bloomery furnace. The combination of factors, using a reducible ore, albeit of poor quality, a high charcoal to ore ratio, and a very high air rate, resulted in strongly reducing conditions and a temperature regime which must be near the maximum practicable in a low clay furnace. In retrospect, it would have been preferable to have smelted a richer ore with a lower charcoal to ore ratio and at a lower air rate to achieve the intended conditions for the production of a good bloom and liquid slags. It is clear that skilled iron workers could, and did, adjust the furnace operating conditions to produce blooms with a higher or a lower carbon content, as required. Ancient iron workers would have been more fully aware of the limitations and possibilities of the resources and the process, which they carried out on a regular basis, than modern researchers can be carrying out occasional experiments.

The role of manganese in the production of bloomery steel has been

the subject of some debate, not yet resolved, in recent years. A question of some importance is whether the manganese merely acts as a catalyser during the reduction, capturing the oxygen more efficiently to make an MnO-rich slag, or whether it played a more significant role and was actually reduced to the metal. Superficially, of course, this ought not to be the case, as MnO will only begin to reduce above 1400°C. However, there are conditions under which an ore rich in MnO and intimately mixed with the iron oxides can be reduced to a Mn-rich white cast iron liquid at 1150°C (Truffaut 2008). Clearly, in a normal bloomery furnace operating at relatively low redox conditions and temperatures there is little question of Mn being reduced. The operating procedures followed in XP92 are of especial interest, since they provided the extreme conditions under which Mn might possibly have been reduced.

One of the main values of experimental iron working is that the conditions under which the metal and slags are formed are known. However, the evidence from the XP92 slags and from the examination and analysis of the metal is somewhat contradictory and is not easy to interpret. At face value the generally low Mn in the metal suggests that most of the Mn would have been oxidized and would have passed directly to the slag. However, as previously described, the slags have consistently high MnO, despite having been smelted from ores of very variable character, and it is clear from the S7 slags and the slag inclusions in the metal that natural homogenization was not taking place to the same extent as with normal fluid bloomery slags (Crew 2000, 39). One mechanism to explain this might be that more Mn was initially reduced into the metal in the strongly reducing conditions in the shaft and that it was subsequently reoxidized in the air blast immediately above the blowing hole. The MnO would then be taken up by the slags, resulting in the homogenization of their MnO content. This could also explain why there was no significant decarburization of the cast iron, or reoxidation of the iron, as it is the Mn which would have been preferentially reoxidized. The oxidation of Mn is a strongly exothermic reaction, which would have raised the temperature above the bloom significantly, perhaps explaining the good metal-slag separation, despite the high melting point of the low-iron slags.

If this was the case, the reduction of the Mn could more easily explain the formation of the discrete areas of white cast iron, from individual pieces of ore rich in MnO. It is of some interest, despite the apparent subsequent reoxidation of most of the Mn, that the white cast iron remains in this form. One mechanism for this may have been that the exothermic reoxidation of Mn locally superheated the white cast iron, which could then have remained liquid to below its freezing point by the phenomenon of undercooling (surfusion), with a subsequent rapid cooling back to white

cast iron. The presence of MnS shows that some of the Mn had remained in a reduced state and had combined with the available sulphur, forming discrete inclusions because of the low solubility of MnS in iron. These inclusions would also have acted as nucleation sites for the graphite.

The Mn content of cast iron from bloomery furnaces has rarely been determined. One exception is the small and well studied piece from Lieporiai, Latvia, which had significant Mn (0.2– 0.45%) and high Si (1.47–4.17%) in discrete trickles of both grey and white cast iron (Navasaitis 2007). The high Si is rather surprising, and this may be due to very localized conditions in the hottest part of the furnace bed, in front of the air inlet. The manganese seems to have been, at least in part, in the form of MnS inclusions. The furnace conditions under which this iron was produced are not known, but were clearly very reducing, and the trickles of cast iron were separated by thin flows of a fluid bloomery slag, with 30–50% FeO and 4– 14% MnO. It would appear that a Mn-rich ore was being smelted under conditions reducing and hot enough to have reduced some of the MnO in the ore, but the high FeO slag suggests the use of a very rich ore and perhaps rather variable furnace conditions which were not so oxidizing in the blowing hole zone, so that some of the Mn remained in the cast iron in its reduced state.

In contrast, XP92 was being blown very hard, with a high charcoal to ore ratio and a very high air rate, thus apparently providing suitable and somewhat paradoxical conditions both for the reduction of Mn and for its subsequent reoxidation. The low Si and Mn in the final iron suggests that their graphitizing and cementizing influence would have been rather limited. With very low Si contents there is a limited range, with Fe and C just below the eutectic composition, in which the different kinds of cast iron can form. This suggests that the cooling rates and compositions of the different XP92 irons may not have been very different, and one model for the formation of the B3 sample would be that it is the result of separate flows of iron of different composition, each cooling at different rates. Further studies are clearly required to resolve these important questions, not least a fuller examination of the bloom from XP92.

The occurrence of cast iron in archaeological contexts has been discussed by numerous authors, most notably by Radomír Pleiner himself (2000; 2001). The recorded cast irons are of a variety of types. Some are small runs of up to a few hundred grams, from bloomery furnaces operating at normal temperatures, which seem to be mainly in the form of the low-melting-point Fe–Fe_3P eutectic. Others are larger accumulations of cast iron, presumably from furnaces being run hard and usually with Mn-rich ores, where the Mn may have played a more active role in the formation of the cast iron.The archaeological cast irons are predominantly

in the form of white cast iron, which must be due to their rapid cooling rate and, in some cases, to the influence of Mn in the ore. In contrast, the XP92 metal seems to have a significant amount of grey cast iron, which is presumably a result of a much slower cooling rate, owing to the large mass and thermal inertia of the main bloom.

In most cases the cast iron has been regarded as a waste product which was discarded because it was not usable. This is not logical, however, as any ancient iron worker faced with pieces of unusable iron would simply have recycled them in a subsequent smelt, so the pieces which are found are those which escaped recycling. This suggests that cast iron might have been a much more regular product than can be recognized from the archaeological record. The example of Llwyn Du is relevant here. It is remarkable that, from the estimated 14,000 smelts carried out, only a very small number of smithing hearth cakes and lumps of discarded metal were found on the excavations. Two of these metallic lumps have been examined and both were high-carbon eutectoid steel surrounded by white cast iron. This shows that strongly reducing conditions and high temperatures were used there, presumably with the intention of producing steely blooms. Most of these waste products, and the presumed metal-rich smithing hearth cakes, would certainly have been recycled, explaining why so few were found at Llwyn Du and their general scarcity from archaeological sites.

There are, of course, examples of cast and high-carbon iron which suggest that some early iron workers made the crucial step towards refining and using this material. The best known case is that of Val Gabbia III (Fluzin 2000), but there are other examples which suggest that the production and use of cast irons and high-carbon steel were more common (Dieudonné-Glad 1997; Mack *et al.* 2000; Salter 2005; Navasaitis 2007; Bauvais 2007; Cech 2008; Leroy *et al.* 2008). Undoubtedly more evidence of this kind will be found as more pieces of 'waste' iron are examined in detail (Salter 1997).

The result of XP92 shows, above all, that cast iron can be produced in a bloomery furnace, in some quantity and without particular difficulty. It suggests also that cast iron should be regarded as an inevitable by-product of bloomery smelting for high-carbon steels rather than as an isolated and exceptional product.

Acknowledgements

These experiments were part of a long series carried out at Plas Tan y Bwlch with the continuous support of our regular team, especially Susan Crew, Ian Devine, Averil Downs, and Sheila Rawson. XP92 was carried

out with the help of Kathy Laws, Ian Brooks, and students from the Institute of Archaeology, University College London, which was facilitated by Thilo Rehren and Michael Charlton. Michael Charlton carried out the XRF analyses of the ores and slags; Philippe Fluzin made the detailed examination and interpretation of the B3 cast iron; Philippe Dillmann and Chris Salter made the analyses of the metal samples. Particular thanks are due to Edmond Truffaut for a great deal of discussion about this experiment and for his insights into the role of manganese in cast-iron production.

Analytical notes

(1) The quantitative bulk chemistries of the ores and slags were determined on pressed powder pellets at the Woolfson Laboratory, Institute of Archaeology, University College London, using a Spectro X-Lab Pro 2000 polarized energy dispersive X-ray fluorescence spectrometer (P)ED-XRF. Each sample was analysed three times along with a range of certified reference materials. The calibration was carried out by the Slag-Fun method developed at the laboratory (Veldhuijzen 2003).

(2) The study protocol was that used in the Laboratoire des Métallurgies et Cultures (UMR 5060 CNRS) at the Université de Belfort-Montbéliard, Sevenans, as described in Fluzin *et al.* 2004.

(3) The SEM-EDS analyses were carried out at the Laboratoire Archéomateriaux et Prévision de l'Altération, Saclay (UMR 5060 and UMR 9956 CEA/CNRS), using a Stereoscan 120 microscope with IdeFIX software, coupled to a Si(Li) detector with a thin beryllium window. The detection limit of Si, P, and Al in the metal is about 0.5%. The detection limit of Mn is about 0.2%. In oxides or silicates, oxygen can be quantified with a relative error of 2%. The accelerating voltage was 15kV. Carbon cannot be quantified and all results are normalized to 100% on the quantified elements.

(4) The SEM-EDX analyses of the S51 and S52 samples were carried out at Begbroke Nano, Department of Materials, Oxford University, using a JEOL 6480LV SEM with the analyses being carried out using an Oxford Instruments INCA EDX system. The detection limits, at 2σ, were 0.08% for Mn and 0.06% for Si.

References

Bauvais, S. 2007, 'Evolution de l'organisation des activités de post-réduction dans le nord du bassin-parisien au second âge du Fer: études multidisciplinaires de la chaîne opératoire en métallurgie du fer', Unpublished Ph.D. thesis, under the direction of P. Fluzin, University of Technology of Belfort-Montbéliard.

Cech, B. 2008, *Die production von Ferrum Noricum am Hüttenberger Erzberg*. Austria Antiqua 2.

Charlton, M. 2007, 'Ironworking in Northwest Wales: an evolutionary analysis', PhD thesis, Institute of Archaeology, University College London.

Crew, P. & Charlton, M. 2007, 'The anatomy of a furnace ... and some of its ramifications', in S. La Niece, D. Hook & P. Craddock (eds.) *Metals and Mines* (London: British Museum), 219- 225

Crew, P. & Crew, S. 1997, Abstracts of *Early Ironworking in Europe: archaeology and experiment* (Plas Tan y Bwlch: Occasional Paper 3).

Crew, P. & Crew, S., 2001, 'Excavations at Llwyn Du, Coed y Brenin, Merioneth, 2001 – woodland management and charcoal processing at a late 14th century ironworks', *Archaeology in Wales* 41, 87-91.

Crew, P. & Salter, C. J. 1991, 'Comparative Data from Iron Smelting and Smithing Experiments', in *From Bloom to Knife, Materialy Archeologiczne* 26, 15-22.

Crew, P. & Salter, C. J. 1993, 'Currency Bars with Welded Tips', in A. Espelund (ed.), *Bloomery Ironmaking during 2000 years* III (Trondheim),11-30.

Crew, P. 1991, 'The experimental production of prehistoric bar iron', *Historical Metallurgy* 25 (1), 21-36.

Crew, P. 1995, 'Decline or Prohibition? The end of prehistoric ironworking in north-west Wales', in P. Fluzin & P. Benoit (eds.), *Palaeométallurgie du Fer et Cultures* (Paris: Edition Vulcain), 217-228.

Crew, P. 2000, 'The influence of clay and charcoal ash on bloomery slags', in C. Cucini Tizzoni & M. Tizzoni (eds.), *Iron in the Alps* (Bienno), 38-48.

Crew, P. 2004, 'Cast iron from a bloomery furnace', *Historical Metallurgy Society News* 57, 1-2.

Crew, P. 2007, 'CaO enhancement in slags: the influence of fluxing or of fuel ash?', in P. Crew & S. Crew (eds.), *Abstracts of Early Ironworking in Europe II: archaeology, technology and experiment* (Plas Tan y Bwlch), 50-52.

Dieudonné-Glad, N. 1997, 'Oulches, a late Roman iron smelting and

smithing workshop', in P. Crew & S. Crew (eds.), *Early Ironworking in Europe, archaeology and experiment* (Plas Tan y Bwlch), 17-20.

Fluzin, P. 2000, 'Ponte di Val Gabbia III (Bienno). Les premiers résultats des études métallographiques', in C. Cucini Tizzoni & M. Tizzoni (eds.), *Iron in the Alps* (Bienno), 24-31.

Fluzin, P. et al. 2004: Fluzin, P., Ploquin, A. & Dabosi, F. 2004, 'Approches métallurgiques et archéometriques', in M. Mangin (ed.) *Le Fer* (Paris: Editions Errance), 113-174.

Leroy, S. et al. 2008: Leroy, S., Desaulty, A-M., Dillmann, P., Tereygeol, F., Verna, C. & Bertrand, L. 2008, 'First examinations of ore, slag and iron artefacts from the iron-making site of Castel-Minier (Aulus-Les-Bains, 09) (France)', in *Proceedings of 2nd International Conference, Archeometallurgy in Europe*, 17-21 June 2007. CD-ROM (Aquileia).

Mack, I. et al. 2000: Mack, I., McDonnell, G., Murphy, S., Andrews, P. & Wardle, K. 2000, 'Liquid steel in Anglo-Saxon England', *Historical Metallurgy* 34, 87-96.

Navasaitis, J. & Selskiene, A. 2007, 'Metallographic examination of cast iron lump produced in the bloomery process', *Materials Science (Medžiagotyra)* 13, 167-173.

Pleiner, R. 2000, *Iron in Archaeology. The European Bloomery Smelters* (Praha).

Pleiner, R. 2001, 'Cast Iron in the European Bloomery period', *Acta Metallurgica Slovaca* 7, 97-101.

Salter, C. J. & Crew, P. 1997, 'High phosphorus steel from experimentally smelted bog-iron ore', in P. Crew & S. Crew (eds.), *Early Ironworking in Europe, archaeology and experiment* (Plas Tan y Bwlch), 83-84.

Salter, C. J. 1997, 'Bloomery Steel – an overlooked material', in P. Crew & S. Crew (eds.), *Early Ironworking in Europe, archaeology and experiment* (Plas Tan y Bwlch), 83-84.

Salter, C. J. 2005, 'Early steel in Britain: introduction, production and use'. Poster presented at *Metallurgy – a touchstone for cross-cultural interaction*, 28-30 April, 2005 (London: British Museum).

Sauder, L. & Williams, S. 2002, 'A practical treatise on the smelting and smithing of bloomery iron', *Historical Metallurgy* 36, 122-131.

Serneels, V. & Crew, P. 1997, 'Ore-slag relationships from experimentally smelted bog-iron ore', in P. Crew & S. Crew (eds.), *Early Ironworking in Europe, archaeology and experiment* (Plas Tan y Bwlch), 78-82.

Smith, K. E. S. 1995, 'Iron-working in North-West Wales in the late fourteenth century'. *Archaeological Journal* 152, 246-290.

Tizzoni, C. C. & Tizzoni, M. 2000. *Il Ferre nelle Alpi* (Bienno).

Truffaut, E. 2008. 'Ferrum Noricum am Hüttenberger Erzberg – Besonderes Erz oder Besonderes Know-How?', in B. Cech (ed.), Die production von Ferrum Noricum am Hüttenberger Erzberg (Wien), 251-271.

Veldhuijzen, H. A. 2003, "Slag_Fun' - a new tool for archaeometallurgy. Development of an analytical (P)ED-XRF method for iron-rich materials', *Papers from the Institute of Archaeology* 14, 102-118.

The Celtic Sword: a source of practical inspiration

J. Lang

Pleiner's work was part of the inspiration behind a series of experiments that the present author undertook between 2003 and 2005 to explore the mechanical properties of differently constructed pre-medieval swords. The variations may have been partly aesthetic, but there were probably practical reasons as well. This paper outlines the results of a series of mechanical tests on modern iron/steel bars forged by the author with different configurations. The conclusions and the limitations of the work are discussed briefly.

Sword - Wrought iron - Steel - Forge welding - Pattern welding - Mechanical testing

Introduction

In his essential work, *The Celtic Sword* (1993), Radomír Pleiner considered his subject 'in the round'. His own extensive metallographic studies were included, of course, together with a comprehensive review of other published material, but he also placed the Celtic sword in its prehistoric, archaeological, and cultural setting. In an innovative initiative, he arranged for a blacksmith to make two swords with dimensions typical of Celtic long swords, in order to investigate the practical procedures and usage of materials employed in sword-making. As he pointed out, the microstructures cannot provide this information, which has important implications for the study of metal working sites and the economics of resources.

Pleiner's work was part of the inspiration behind a series of experiments that the present author undertook between 2003 and 2005 to explore the mechanical properties of differently constructed pre-medieval swords. Pleiner's study made it very clear that several different arrangements of metal strips or bars were used during the Iron Age, a practice which eventually developed into pattern welding. The reason for this may have been partly aesthetic, but there were probably practical reasons as well. In tribute to the inspirational work of Radomír Pleiner, this paper outlines the results of a series of mechanical tests carried out on forged

iron/steel samples made in different configurations and briefly discusses the conclusions and the limitations of the work.

Metallography and its limitations in the study of metallic artefacts

Apart from radiography, the most common method of examining metallic artefacts such as swords is to study their microstructure. This entails removing a small sample to mount, polish, etch, and examine. The selection of the sample site is often determined by the state of the metal and the absence of organic materials such as wood or cloth, which may give information about scabbard linings or cloth wrappings. The section provides information on the metal, its composition (by analysis), and the construction and number of components. The heat treatment, carburization, and final state may be determined, as well as the hardness, which gives some indication of the mechanical properties. Inclusion analysis may give information about the ore type and the extraction process. However, as Pleiner himself has said (1993, 134–35), a small half-blade cross-section may be unrepresentative of the blade as a whole: with this caveat in mind, such a section can still tell us something of the technological knowledge utilized by the smith.

Metallography provides much useful information, but it only sheds a peripheral light upon the economics of time, labour, and resources. For these, different insights are required, as Pleiner showed in his cooperation with a smith. It should be accepted, of course, that current attitudes to these considerations are unlikely to have obtained in the past and, in any case, cultural or social changes may influence production, in ways which are not always easy to discern. It has been suggested, for example, that sometimes items intended for burial were specially made and could be basic and of poor quality (Moir 1990, 68). On the other hand, some of the unique and splendid items found were clearly of value and significance to the person with whom they were buried and their society, for example the elaborate Kirkburn sword, found in an Iron Age chariot burial in Yorkshire (Stead 2006, 184–85, 251–53).

The replica blades which Pleiner's experienced blacksmith and others, such as Hector Cole in the UK, have produced, can give us an idea of the time and materials involved in making different types of swords, or other items such as spearheads, especially when allied to experimental information on the extraction processes which have been discussed and listed by Pleiner himself (2000) in relation to experiments in smelting and ferrous metal production by Crew (1991) and others.

Smithing experiments: comparison of construction regimes

Different arrangements of components have been observed in pre-medieval swords and characterized by Pleiner (1993, 141,146,148). Simplified, the main arrangements were (i) the use of a single piece of metal, (ii) the use of two or more components, laid one on top of each other, like a long sandwich with joins from edge to edge of the blade, (iii) the use of two or more components, laid side by side with joins from surface to surface, (iv) the use of twisted components, as in pattern welding. There might be a number of reasons for using different arrangements, such as making use of the available materials. Since swords were usually functional objects, the question might also be asked: was there any mechanical advantage to be gained in the different regimes?

To investigate the mechanical behaviour of the different arrangements, a number of simple experiments were carried out, using two types of modern wrought iron and modern steel, in the form of strip. The alloys were chosen because they were readily available, although ideally bloomery products should have been used, including phosphoric iron. Impact, tensile, and bend tests were carried on the test bars. Microsections were examined and the mounted samples were microhardness tested (DPH_{100}).

The metal was tested as far as possible in the 'as received' condition and also after fire-welding in various combinations (Table 20). The majority of the bars were forged by the author, but three experienced blacksmiths (David Sim, Hector Cole and Mick Maxen) each made two composite twisted bars with TWI (commercial wrought iron) and BlS (commercial black steel) in order to act as a check on the use of different conditions under which the smiths worked. These included the use of a coke hearth, similar to the author's (Sim), a charcoal and coke hearth (Cole) and a propane gas furnace (Maxen). The test results showed little difference between the smiths. The test bars were left to cool down in air on the bricks near the hearth at the end of fabrication.

The mechanical tests

The tensile test results (Table 21) showed a not unexpected rank order, with the as-received steels having the maximum tensile strength and pure wrought iron the lowest values.

Using data from the tensile tests it was also possible to calculate the elasticity (or springiness) of the test material. The elastic energy to yield was lowest for the wrought irons, followed by the composites, while the two steels were able to absorb the most elastic energy before yielding (Table

Table 20: Summary List of samples and tests.

type (AR, B)	type B	TWI	PWI	Br S	Bl S	e to e	s to s	twist	tensile	impact	bend	micro	quench
AR			1			1			1		1	1	
AR		1				1			1		1	1	
AR					1	1			1		1	1	
B	1	2				2				2		2	
B	1		4			4				3	1	4	
B	1			2		2				2		2	
B	1				1	1				1		1	
B	2	1		1		1				1	1	1	1
B	2	1			1		1				1	1	
B	2	3			3	3					3	3	
B	2		2	2			2		1	1	1	2	
B	2		2	2		2			2	2		2	
B	2		5	5		5			4	5	1	5	
B	2		1		1	1					1	1	
B	3	15			15			15	2	10	8	15	7
B	3		1	1				1			1	1	

Key: **AR** as received, **PWI** pure wrought iron (low slag content), **BrS** bright steel (EN 10025 S 275), **BlS** black steel (EN 3B 080A15), **e to e** edge-to edge joins, **s to s** surface-to surface joins, **twist** composite made of twisted bars, **Type B1** composite made from 3 bars of the same metal, **Type B2** composite made from 3 alternating strips of different metal, **Type B3** composite made by twisting and welding two B2 bars together, **tensile**, **impact** (Charpy) and **three point bend** mechanical tests, **micro** microsection examined by microscopy, hardness tested, **quench** heat treated samples, rapid oil cool (microsections, hardness and impact tests)

22). As springiness was a valued property in swords, it is easy to see why steel was utilized in sword-making.

In order to see how easy it might be to bend a sword (they are often excavated in this state), the force (F) used to bend a bar was calculated from the tensile test data (Table 23), using the formula (where Y is the yield stress, b the width, d the thickness, and L the length)

$$\text{F (force to bend)} = bd^2\text{Y/L}$$

Table 21: Results of tensile tests, N/mm^2 (rank order).

	Br Steel AR	Bl Steel AR	B3*	B2#	TWI	PWI
No. of samples	1	1	3	9 (SDev)	1	1
Average gauge length, mm	48	56	51	25	56	56
YS	517	335	292	270 (73)	228	192
UTS	569	489	394	394 (74)	329	273

* B3: Three alternating strips of black steel and TWI welded together, twisted and then welded to another similar bar (TWI, Bl S, TWI; Bl S, TWI, Bl S)

B2: Alternating strips of bright steel (BrS) and PWI (pure wrought iron) welded together, edge to edge joins AR: as-received SDev standard deviation

Table 22: Elastic energy to yield, MJ/m^3 (rank order).

bright steel	black steel	B3 TWI/BlS	B2 PWI/BrS	TWI	PWI
7.0	3.8	3.12#	2.8*	1.2	0.7

average of 3 results, * average 7 results, standard deviation 0.72

Depending on the stance, it is possible for a young healthy male without specialized training to raise a load of 400N from the ground to waist height without excessive strain (Anderson & Chaffin 1986). The results show that it might not have been difficult to bend some Iron Age and Roman swords. From the formula it is easy to see that longer swords (assuming that they could be grasped at either end) were easier to bend than shorter swords of the same breadth and thickness. Increasing the thickness increased the force required considerably.

Table 23: Force to bend a bar, N (rank order).

breadth × depth × length, mm	bright steel	black steel	B3 TWI/BlS	B2 PWI/BrS	TWI	PWI
40 × 4 × 500	610	429	375*	315#	292	246
48 × 4 × 825	487	312	272	229	212	179
48 × 5 × 825Ω	765	489	427	359	332	280

B3 and B2 average values, * standard deviation 39, # standard deviation 23
[Dimensions of the Orton Meadows sword 97 Ω d increased to 5mm]

Charpy impact test results, carried out at room temperature (19-22°C), showed a marked difference, depending on whether the impact was parallel (P) to the joins or at right-angles to them (T) (Table 24), the former being more resistant. The two types of wrought iron showed a marked difference in impact behaviour, which is clearly a result of the presence of inclusions (Fig. 110 /Plate XXXI/). The small grain size (9–5 on the American Society of Metals ASTM system) of the BrS (commercial bright steel) probably also contributed to the better impact behaviour in comparison with BlS, which has a larger grain size (2–4 grain size, ASTM).

Table 24: Results of Charpy impact tests on composite bars, J (rank order).

bar type	AR	AR	AR	twisted B3	non-twisted B2†	non-twisted B2	twisted B3	AR
materials	PWI	BrS	BlS	TWI, Br S	PWI, Br S	PWI, Br S	TWI, Bl S	TWI
P						161 (5)	132 (3)	
T	147 (2)	110 (2)	88 (1)	81 (2)	56 (1)	45 (4)	54 (18)	39 (2)

The tests were not carried out on the same day. †surface to surface joins. Number of samples in ( )

It was noted that a test specimen that had been heated inadvertently

within the austenitizing range for three or four minutes became completely martensitic after water-quenching, and showed negligible resistance to impact, thus demonstrating the control that is required to make best use of heat treatment, including tempering, and perhaps why it is rarely seen in Iron Age swords, although contemporary tools were heat treated (Fell 1993; 1997).

The bend test (Table 25) provides an indication of the ductility of the material and is probably the most useful of all the common mechanical tests available to compare different configurations of materials used to make sword blades because literary evidence (e.g. Polybius 30, 33, 114) suggests that the La Tène warriors frequently had problems with their long slashing swords which bent during the course of a battle. This was a fatal flaw, according to the classical writers. As the archaeological record shows, swords often appear to have been bent deliberately before deposition and sacrifice.

The figures given in Table 25 show that TWI deformed most readily under loading, whereas BrS required more than twice the load to reach the yield point. The twisted bar composites were more resistant to bending than BlS and the other combinations. When composite bars were forged to a lens-shaped cross-section, this had the effect of increasing the bend stress by 30–40%.

Table 25: Results of three-point bend test (MPa) (rank order).

type	BrS	B3	AR	B2	B2	AR	AR
		TWI/BlS	BlS	TWI/BlS	PWI/BrS	PWI	TWI
MPa	688	469	453	396, 371†	394, 367†	374	305
no.		7		4, 1†	4, 1 †		

† results for bar with surface to surface joins

Time and resources were limited in this study, the number of samples was small, and the metals used were modern alloys. Modern steels did not produce similar welds to those found in ancient artefacts, unlike welds between wrought-iron strips, which did. The presence of manganese in the steel appears to have affected the nature of the welds (Fig. 110 /Plate XXXI/, Fig. 111). The same phenomenon was observed by the author in welds made by Hector Cole, who specializes in making swords and other items, mainly in a charcoal-fuelled hearth, but using modern mild steel. Analyses suggest that the minute slag globules in the joins may result from the presence of manganese in the metal. As slag inclusions affect impact resistance, the behaviour of the welds might not represent the likely behaviour of joins on ancient swords.

The results suggest that laminating bars of wrought iron with steel

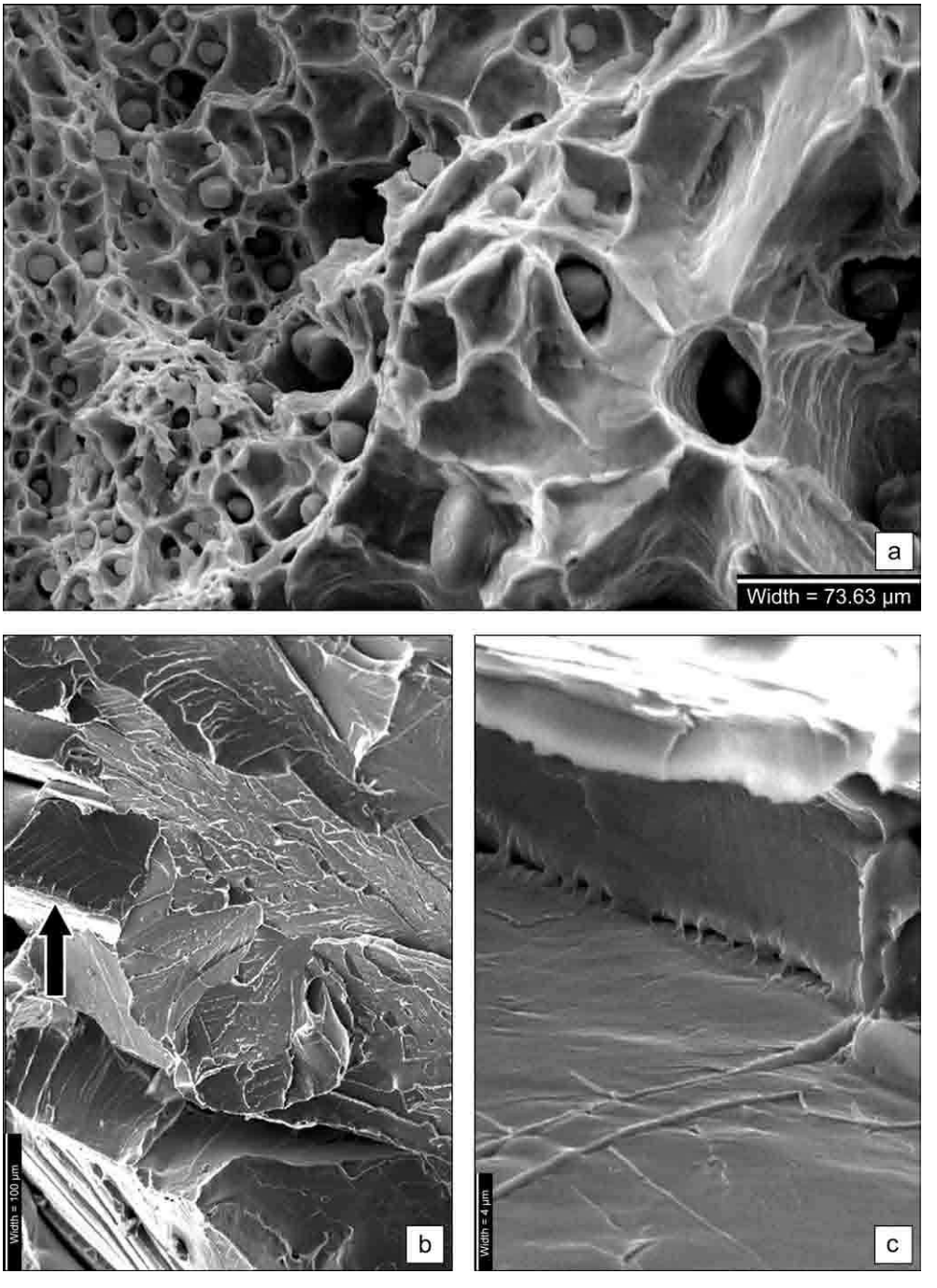

Figure 110: SEM micrograph (a) brittle fractured surface, weld on left, TWI on right. Note the globular slag, (b) cleavage fracture in PWI (magnification bar 100μm), (c) enlargement of crack initiating (magnification bar 4μm).

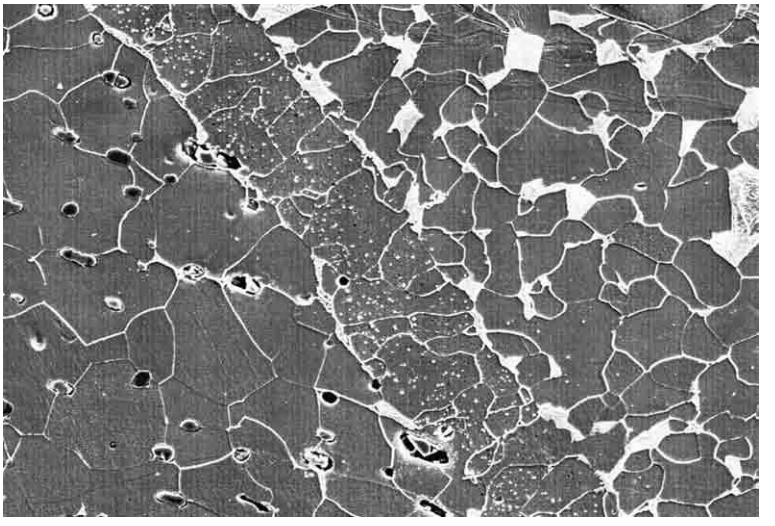

Figure 111: Weld between TWI (left) and BlS (right), slag/oxide and pearlite at the edge of the weld, globules within the weld and close to it. (Field of view 0.66mm).

improves tensile properties and resistance to bending, but has less effect on impact, where the influence of the inclusions and composition were more marked. Williams (2003, 932, 940) also found that increasing the slag content decreased fracture toughness. The orientation of the joins, relative to the direction of an impact, may have had an effect on the impact resistance, but the data were insufficient. The use of twisted bars did appear to improve the resistance to bending stress. Overall, the use of composites had the advantages of increasing the strength of the weaker materials and improving resistance to bending. Once steel became more available and its treatment better understood, the complex constructions lost some of their *raison d'être*.

While it is acknowledged that only simulacra of past objects can be produced and the reasons why they were made in a particular way may remain elusive, further research remains to be done, for example, on the role of phosphoric iron in the composites. In our attempts to understand as much as possible about the ancient ferrous artefacts, we all owe a great debt to studies such as *The Celtic Sword*, the two volumes *Iron in Archaeology*, and the many papers contributed by Radomír Pleiner. I would like to express my gratitude for the information and ideas which his works have given me over the years.

Acknowledgements

At the University of Reading, the author would like to thank Dr Richard

Chaplin for valuable advice and guidance and John Frew for advising on the mechanical testing, and at the British Museum Dr Sheridan Bowman and Dr David Saunders for allowing me to carry out the metallographic work and Nigel Meeks for helping with SEM work. Thanks are also due to Dr D. Sim, Hector Cole, and M. Maxen for help and advice on smithing.

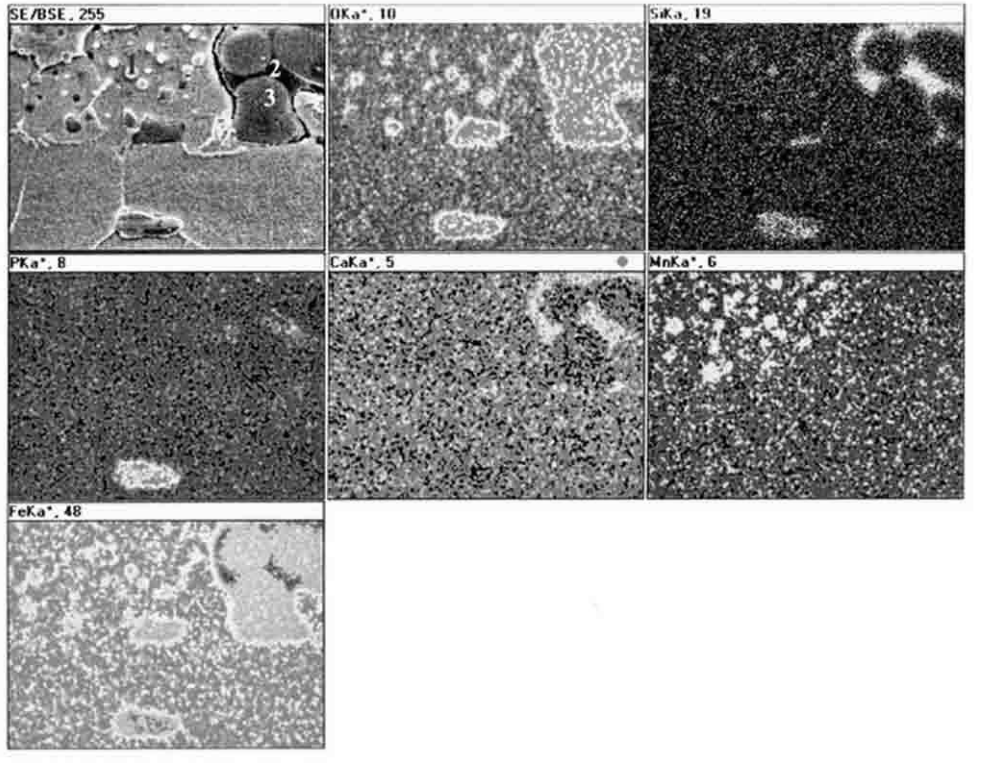

Figure 112: Elemental distribution map from top left: secondary electron image, oxygen, silicon, phosphorus, calcium, manganese, iron. Analysis (EDXA-SEM), weight-% as oxide.

	Al_2O_3	SiO_3	P_2O_3	SO_3	K_2O	Cr_2O_3	MnO	FeO	CoO
1. Globule	nd	1.8	nd	nd	nd	0.9	8.5	87.4	0.8
2. Slag matrix	1.1	20.5	3.9	0.4	0.4	4.2	nd	65	nd
3. Slag 2^{nd} phase	1.2	15.1	2.3	1.2	nd	2.8	2.0	74	0.7

nd: below detection limits
Detection limits are less than 0.07% for all elements analysed (except iron)
The precision is taken to be 2σ, which is 1.5% or less for iron and less than 0.5% for other elements. The accuracy is $\pm$ 1-2%.

References

Anderson, C.D. & Chaffin, D.B. 1986, 'A biomechanical evaluation of five lifting techniques', *Applied Ergonomics* 17 (1), 2-8.

Bradley, R. 1998, *The Passage of Arms* (Oxford).

Crew, P. & Salter, C. 1991, 'Comparative data from iron smelting and smithing experiments', *Materiały Archeologiczne* 26, 15-21

Fell, V. 1993, 'Examination of four Iron Age ferrous hammer heads from Bredon Hill (Hereford and Worcester), England', *Journal of the Historical Metallurgy Society* 27(2), 60-70.

Fell, V. 1997, 'Iron Age files from England', *Oxford Journal of Archaeology* 16(1), 79-98.

Moir, D. 1990, 'The metallography and scanning electron microscope analysis of nine spearheads from the Anglian cemetery at West Heslerton, North Yorkshire', Unpublished dissertation (University of Bradford).

Pleiner, R. 1993, *The Celtic Sword* (Oxford).

Pleiner, R. 2000, *Iron in Archaeology. The European Bloomery Smelters* (Praha).

Pleiner, R. 2006, *Iron in Archaeology: Early European Blacksmiths* (Praha).

Polybius, *Histories*, Trans. W.R. Paton 1922-7 Loeb series.

Stead, I.M. 2006, *British Iron Age Swords and Scabbards* (London).

Williams, A. 2003, *The Knight and the Blast Furnace* (Leiden – Boston).

Index of places

Aalborg, Denmark, 55, 56, 292
Adamov, Czech Republic, 74, 76, 101, 296
Aistrup, Denmark, 56, 292
Akset, Norway, 90, 298
Amiens, France, 173, 176, 178, 187–194, 283, 310
Aquincum, Hungary, 67
Arrabona, Hungary, 67
Avignon, France, 173, 194

Balaton, Hungary, 65, 68
Baszowice, Poland, 47
Bátaszék, Hungary, 67, 71
Bayern-Württemberg, Germany, 64
Beauvais, France, 173, 175, 177, 183–186, 194, 283, 308
Bila Cerkva(Біла Церква), Ukraine, 107
Bílina, Czech Republic, 138
Blansko, Czech Republic, 73, 76
Bodrog, Hungary, 70
Bodrog-Alsóbű, Hungary, 68
Bohemia, Czech Republic, 77, 83, 84, 125, 137–139, 147–151
Bradford, England, 94
Brescia, Italy, 163
Březno, Czech Republic, 3
Brigetio, Hungary, 67
Brno, Czech republic, 76, 77, 83, 102
Brwinów, Poland, 35, 45, 47, 289, 290
Budalen, Norway, 90
Budeč, Czech Republic, 142, 148
Bull's Rock cave (jeskyně Býčí skála), Czech republic, 101–103, 106, 281, 300
Burdale, England, 123–125, 127–135, 281, 303
Burgenland, Austria, 32
Burgundy (Bourgogne), France, 225, 227, 311
Buštěhrad, Czech Republic, 43

Cambridge, England, 164, 174
Chernigov (Чернигов), Ukraine, 153–155, 159, 203, 282
Churburg, Italy, 163, 164, 166–172, 282, 306

Dokkfløy, Norway, 92, 299
Dorset - Bestwall, England, 124
Dubany, Czech republic, 139
Duchcov, Czech Republic, 138
Dunaújváros, Hungary, 67

Engsbach, Germany, 61, 62
Espe, Denmark, 57, 60, 61, 293
Espevej, Denmark, 55, 279

Flixborough, England, 124, 132
Fyresdal, Norway, 93, 299

Garbacz Skała, Poland, 50, 291
Gardzienice, Poland, 32
Gera-Tinz, Germany, 60–62
Gnezdovo(Гнёздово), Russia, 154, 157, 159
Gorsium, Hungary, 67
Győr, Hungary, 67

Habrůvka, Czech Republic, 74, 77
Hamwic, England, 123–125, 131, 132, 134, 281
Heglesvollen, Norway, 88, 90
Helgö, Sweden, 125
Herning, Denmark, 58, 62
Holsted, Denmark, 57, 58, 292, 293
Hrabišín, Czech republic, 138
Hrdlovka, Czech Republic, 137–140, 142–145, 147–149, 151, 282

Iberian Peninsula (Península Ibérica), 176, 195
Isernbarg, Germany, 43

Jämtland, Sweden, 90
Josefov, Czech Republic, 74

Kaposvár, Hungary, 66, 67
Kaposvár-Fészerlak, Hungary, 65, 67
Kemerovo (Кемерово), Russia, 200
Kiev (Київ), Ukraine, 153, 155, 200, 203
Košice, Slovak Republic, 108
Kraków, Poland, 31, 32, 35, 38, 279
Krutik (Крутик), Ukraine, 154
Kunów, Poland, 32, 47
Kútvölgyi, Hungary, 66

Lahovice, Czech Republic, 149–151
Langental, Austria, 32
Lizawice, Poland, 43
Llwyn Du, Wales, 239, 240, 243–246, 258, 285
Lombardy, (Lombardia), Italy, 163
Łomno, Poland, 47, 48
London, England, 3, 259, 278
Lussonium, Hungary, 67

Magyaratád, Hungary, 66, 67
Magyaratád-Kéri, Hungary, 67
Malaya Kopanya (Малая Копаня), Ukraine, 107–109, 113, 118–121, 281
Malaya Kopanya - Chellenica (Малая Копаня - Челленица), Ukraine, 108, 113, 116, 119, 121
Malaya Kopanya - Serednij Grunok (Малая Копаня - Середний Грунок), Ukraine, 108, 112, 113, 115, 119, 121
Malín, Czech Republic, 148–150
Marcinków, Poland, 47
Mazovia, Poland, 41, 43–47, 49, 279, 290
Midtre Gauldal, Norway, 89
Milan (Milano), Italy, 163, 171, 282
Minsk (Минск), Belorussia, 200
Mirogonowice, Poland, 47
Młochów, Poland, 35, 289
Moravian Karst (Moravský kras), Czech republic, 73–85, 102, 280, 297
Moscow (Москва), Russia, 153, 200, 218, 219, 283
Mursa, Croatia, 67

Newcastle, England, 3
Novgorod (Новгород Великий), Russia, 125, 154, 203, 212, 215, 218, 219
Nystaul, Norway, 95, 96

Óbuda, Hungary, 67
Olomouc, Czech republic, 77, 82, 150
Olomučany, Czech republic, 74, 77–81, 83, 84, 297
Ontcheshty (Ончещты), Ukraine, 107
Ore Mountains (German: Erzgebirge, Czech: Krušné hory), Germany, Czech Republic, 138
Ořech, Czech republic, 60–63
Osek, Czech Republic, 139
Osijek/Eszék, Croatia, 67
Oslo, Norway, 93, 95
Østland, Norway, 90, 92
Ószőny, Hungary, 67

Paks, Hungary, 67
Pannonia, 65, 67, 70, 279, 280
Pécs, Hungary, 67
Picardy, France, 173, 176, 180, 193, 283
Plas Tan y Bwlch, Wales, 239, 258, 285
Podchełmie, Poland, 47
Pokrzywnica, Poland, 47–50, 291
Prague (Praha), Czech Republic, 3–5, 32, 60, 63, 76, 144
Pskov (Псков), Russia, 200, 203, 218, 219

Ramsbury, England, 124
Ratenice, Czech Republic, 43
Ribe, Denmark, 57, 58, 292, 293
Rudice, Czech Republic, 74
Rudki, Poland, 32, 35, 289
Ryazan (Рязань), Russia, 203

Ságvár, Hungary, 67
Saintes-Maries-de-la-Mer, France, 228, 312
Sarskoye (Сарское), Russia, 154
Savaria, Hungary, 67
Sekanka, Czech republic, 149, 150
Shestovitsa (Шестовица), Ukraine, 153–157, 159, 160, 282
Singsås, Norway, 89
Skały, Poland, 47
Skarżysko-Kamienna, Poland, 50, 291
Skovmark, Denmark, 55–59, 61–63, 279, 292
Snejbjerg, Denmark, 58, 62
Soissons, France, 173, 175–177, 179, 180, 182, 183, 194, 283, 308
Solotvyno (Солотвино), Ukraine, 107
Somogy, Hungary, 65–67
Sønder Holsted, Denmark, 55, 57–60, 62, 279, 292, 293
Sopiane, Hungary, 67
Sopron, Hungary, 65, 68–71, 280, 294, 296
Southampton, England, 124
Stará Boleslav, Czech Republic, 144, 146, 148, 150
Staraya Ladoga (Старая Ладога), Russia, 154, 216
Suzdal (Суздаль), Russia, 203, 218
Świętokrzyskie Mountains (Góry Świętokrzyskie), Poland, 32, 34, 35, 41, 43, 45, 47–50, 279, 289, 291
Szombathely, Hungary, 67

Tác, Hungary, 67
Tarczek, Poland, 50, 291
Telemark, Norway, 93, 95, 299
Thuringia, Germany, 60
Tolna, Hungary, 67
Transdanubia, Hungary, 65, 66, 279
Tricciana, Hungary, 67
Trøndelag, Norway, 88, 89, 91, 298
Tver (Тверь), Russia, 218, 219

U kukačky, Czech Republic, 77–79
Ulyanovsk (Ульяновск), Russia, 200
Uničov, Czech Republic, 82

Valcum, Hungary, 67
Veum, Norway, 93, 299
Vinje, Norway, 95, 96
Vladimir (Владимир), Russia, 218

Wharram Percy, England, 123–128, 130–135, 281, 304

Wolkenberg, Germany, 39
Worowice, Poland, 47
Wronów, Poland, 35, 47, 289

Yekaterinburg (Екатеринбург), Russia, 200
York - Coppergate, England, 124, 131–133, 304
York - Fishergate, England, 124, 131
York, England, 123–125, 130–134, 281, 304

Zabrušany, Czech republic, 138
Zamárdi, Hungary, 65–67
Zamárdi-Kútvölgy, Hungary, 65–67
Zamárdi-Rétiföldek, Hungary, 66
Želechovice, Czech republic, 77, 79, 81–83
Zemplín, Slovac republic, 107, 108, 119
Zlončice, Czech republic, 137, 144, 146–151, 282, 305
Zvenigorod (Звенигород), Russia, 218

SOUHRN

Kniha *Archaeometallurgy of iron - Recent Developments in Archaeological and Scientific Research* vznikla z iniciativy a za přispění řady badatelů zabývajících se archeologickým anebo vědeckým výzkumem starého evropského hutnictví, kovářství a související problematikou. Hlavní impuls vzešel z potřeby intenzivnější vzájemné komunikace a výměny nejnovějších a zásadních výsledků v této oblasti mezi badateli západní a východní Evropy, stejně jako z potřeby zachytit historický vývoj samotné archeometalurgie - interdisciplinární vědní disciplíny, v níž se prolínají archeologie, historie, kulturní antropologie a materiálové inženýrství. Využita byla také možnost připojit blahopřání k osmdesátým narozeninám profesora Radomíra Pleinera, který se nebývalou měrou zasloužil o celosvětový rozvoj oboru a jehož práce a úsilí dlouhodobě vytvářely most mezi západo- a východoevropskými odborníky a výsledky jejich práce. Autoři s hrdostí tuto knihu Radomíru Pleinerovi věnují.

Knihu symbolicky zahajuje oddíl přibližující Pleinerovu životní pouť a dílo. Následují odborné statě, rozřazené do oddílů reprezentujících významnější okruhy archeometalurgického bádání a respektujících celkovou skladbu příspěvků: 1) poznámky ke starověkým železářským pecím a k vývoji starého železářství v evropských regionech, 2) příklady výzkumu evropských archeologických a historických výkovků, 3) příklady zapojení archeometalurgie do archeologického, historického a historicko-technologického bádání, a konečně 4) příklady experimentu v archeometalurgii. Pro českého čtenáře předkládáme k rychlejší orientaci česká abstrakta jednotlivých statí.

Radomír Pleiner: magister ferrariarum v osmdesáti *(H. Cleere)*
Radomír Pleiner se narodil 26.4.1929 v rodině akademického malíře a legionáře Vladimíra Pleinera. Po středoškolském studiu (gymnasium Velvarská, Praha Dejvice) byl přijat na studium prehistorie a historie na Fil. fak. KU Praha – PhDr v r. 1952. Od roku 1953 pracoval jako vědecký aspirant při Arch. Ústavu ČSAV v Praze, kde r. 1955 dosáhl vědecké hodnosti CSc. Dále působil v Archeologickém ústavu jako vědecký pracovník, pověřený výzkumem nejstaršího hutnictví železa. Oženil se v r. 1955. Aplikoval metalografii ve výzkumu nejstarších kovářských technik a zasadil se o zřízení metalografické laboratoře v ARÚ (1963). Na mezinárodním kongresu Unie prehistorických a protohistorických věd v r. 1966

prosadil ustavení konzultativního orgánu Comité pour la sidérurgie ancienne de l'UISPP a valným shromážděním této Unie byl zvolen sekretářem. Účastnil se terénních a experimentálních akcí v zahraničí (Polsko, Rusko, Anglie, Skandinávie, Rakousko, Německo, Francie) a tématických symposií a konferencí. V letech 1966 a 1968 byl členem amerických expedic do Íránu a Afghánistánu, čehož využil, stejně jako půlročního stipendia ve Spojených státech (1971), k vypracování čtyř studií o železářství na Předním a Středním východě, které se staly základem jeho doktorské disertace (DrSc. 1981). V r. 1968 byl jmenován docentem a v r. 1992 profesorem prehistorie na Karlově universitě v Praze (přednášky o pravěké technologii). Od r. 1993 v důchodu. Je dopisujícím členem Deutsches Archäologisches Institut v Berlíně, Historical Metallurgy Society v Londýně a Unité propre du CNRS v Belfortu-Sévennans. Je čestným členem Society of Antiquaries, London (Hon. FSA) a Společenstva uměleckých kovářů a zámečníků a kovářů-podkovářů Čech, Moravy a Slezska. Je autorem nebo spoluautorem dvanácti knih a bezmála 250 studií a článků.

1) Poznámky ke starověkým železářským pecím a k vývoji staré-ho železářství v evropských regionech

Nový pohled na starověké železářské pece se zahloubenou nístějí

(K. Bielenin)

Starověké železářské pece se zahloubenou nístějí patří mezi základní zařízení hutní technologie užívané ve starověké Evropě za hranicemi římské říše. Hlavní komponentou těchto pecí, která přetrvala staletí a je základním prvkem výzkumu, je struskový blok - odpadní produkt, který se zformoval v dolní části pece, tzv. zahloubené nístěji. Hutníci dosáhli s užíváním těchto pecí významného pokroku majícího velký dopad na další staletí. Vymoženost pece spočívala v odvedení strusky z redukční zóny pece do speciálně připravené jámy (viz Fig. 3: a, b, c). V důsledku toho mohl starověký hutník odloučit strusku od formující se železné houby a získat tak železný blok připravený k prokování. Zvýrazněné části na povrchu struskového bloku (viz Fig. 4) obsahují místa vystavená plynulému tuhnutí. Tyto části prokazují existenci zóny formování metalického železa bez přítomnosti strusky. Navíc, získaný produkt nebyl konglomerát strusky a železa jako v případě experimentálního výzkumu, ale železná houba bez strusky, typická pro pece s odpouštěnou struskou. Železná houba z takové pece nevyžaduje tzv. post-redukční fázi, jak se doposud předpokládalo. Prezentované výsledky, vyplývající z analýzy plynule ztuhlého povrchu

struskového bloku, a nový zorný úhel pohledu na tuto železářkou pec jsou v současné době předmětem verifikace a metalurgického výzkumu na AGH hornicko-hutnické univerzitě v Krakově.

Nístějové kanály a jejich role v přímé výrobě železa na příkladu pecí převorské kultury z území Polska *(S. Orzechowski)*
U některých železářských pecí převorské kulturní oblasti byly objeveny různé typy bočních kanálů spojujících zahloubenou nístěj s okolním zemských povrchem. Jde o pozůstatky zařízení podporujících řádný systém vhánění větru v úrovni šachet pecí. Takovýchto podpůrných zařízení bylo rozpoznáno několik typů, počínaje jednoduchým bočním rozšířením nístěje až po pravidelné, miskovitě tvarované kanály. Jejich užívání nebylo běžné, přestože v některých regionech – především v Mazovsku – bylo jimi v různých obdobích vybaveno 10 až 15 % pecí. Původně se předpokládalo, že tyto kanály napomáhaly vysoušení nístěje a zlepšovaly tah větru pouze v počátečním stádiu tavby. Četné vzorky pecí z Mazovska a oblasti Svatokřížských hor nicméně naznačují, že jejich role v tomto stadiu nekončila, a že podporovaly chod pece v celém procesu tavby.

Nejstarší železářské pece v Dánsku *(A. Jouttijärvi, O. Voss)*
Nejstarší dánská železářská pec byla objevena roku 1966 ve Skovmarku, v severním Jutsku, a pomocí radiokarbonové metody byla datována do let 90 až 110 n.l. Pec měla v nístěji hrudní otvor ústící do pracovní jámy. V roce 1986 byla v Espeveji, v Západním Sealandu, nalezena další pec stejného typu, a to společně s jednotlivými hliněnými hrudními štíty, které však nebyly nalezeny in situ. Rekonstrukce této pece byla následně vypublikována, viz Fig. 18. Hrudní štít se nacházel v blízkosti pecní nístěje s níže umístěným otvorem pro odstranění strusky. V předložené stati je představena nová rekonstrukce této pece, Fig. 17, založená na archeologickém výzkumu pece typu Skovmark v Sønder Holstedu v jižním Jutsku v roce 2000. Autoři přicházejí s teorií, že původ pecí typu Skovmark lze hledat již v laténských pecích jihu Německa.

Některé výsledky a problémy maďarské archeometalurgie *(J. Gömöri)*
Při stavbě dálnice v Transdanubii byla archeologicky prozkoumána nově objevená rozsáhlá avarská železářská centra. V této části Panónie byla dvě významná období železářské výroby: starší je spjata se středním a pozdním obdobím Avarské říše (od 7.-8. stol.) a dobou karolinskou (9. stol.); novější se vznikem maďarského státu v 10. stol. Až doposud byly známy pouze dvě lokality, na kterých byly nalezeny pece z obou uve-

dených období. První vývody nejnovějšího archeometalurgického výzkumu nasvědčují, že avarské železářství bylo v Panónii důležitější než jsme předpokládali. Tato rozsáhlá centra železářské a kovářské výroby (snad zbraní) mohla ležet přímo v zóně avarského vojenského uskupení organizujícího vojenské tažení proti Byzanci na trati hlavních římských cest. Vyvstala i další otázka: kde v Panónii hledat počátky avarské železářské výroby? Podle současných znalostí nemá tato výroba žádnou místní tradici doby římské. Jeden z výsledků nového archeologického výzkumu je korekce datování domnělé římské pece v Sopronu do 11. až 12. století.

Některé aspekty vývoje velkomoravského železářství *(V. Souchopová, J. Merta a O. Merta)*
Příspěvek přináší některé z poznatků z uzavírající se etapy intencionálního výzkumu hutnictví železa ve střední části Moravského krasu, který započal v 60. letech minulého století. Obsahuje stručnou historii průběhu projektu, určení a datování typů pecí i dílen a z toho vyplývající zjištění jejich časoprostorového rozmístění a způsobu jejich řízení. K posunu došlo v otázce postavení tohoto těžebně–hutnického revíru, který přes své geografické umístění odpovídá rozsahem a produktivitou práce specializované výrobě, přiřazované velkomoravským mocenským centrům. Výroba a distribuce železa v této důležité předindustriální řemeslné oblasti podléhala pravděpodobně některému z velkomoravských center a komunita hutníků i jejich zázemí patřila zřejmě k čeledi (familia) některého z velmožů té doby.

Norsko jako producent svářkového železa *(A. Espelund)*
Archeometalurgický výzkum přímé výroby železa a výrobních lokalit v Norsku, vedený zhruba od roku 1982 a značně podpořený možnostmi radiokarbonového datování, vedl k novému pohledu na tyto aktivity. Velké šachtové pece se zahloubenou nístějí byly užívány zhruba od r. 300 př.n.l. až po r. 600 n.l., menší šachtové pece s bočním odpouštěním strusky cca od r. 700 do r. 1300, a nejnovější – zahloubené pece bez vypouštění strusky od r. 1400 do r. 1800 (u těchto pecí představuje využití umělého tahu v prvotním údobí tavby, realizovaném přímým vsázkováním dřeva a jeho transformací na dřevěné uhlí, pozoruhodnou alternativu vůči konvenční představě o provozech pecí vyžadujících dřevěné uhlí a měchy). Změny technologie někdy mezi lety 600 až 800 n.l., stejně jako kolem let 1300 až 1400, kladou tíživé otázky. Autor se zabývá, byť ne přímo v předložené stati, možnostmi řízení obsahu uhlíku v kovu produkovaném ve všech třech výše uvedených typech pecí (řízení obsahu uhlíku pomocí kontroly vnitřního objemu pecí, dvoustupňovým procesem tavby a pomocí řízené délky tavby).

2) Příklady výzkumu evropských archeologických a historických výkovků

Chemická a metalografická analýza prehistorického prstence z jeskyně Býčí skála *(K. Stránský)*
Příspěvek předkládá výsledky metalografického a chemického rozboru prehistorického dutého prstence (6. stol. př.n.l.) z jeskyně Býčí skála. Na základě výsledků rozborů lze konstatovat, že struktura fragmentu prstence sestává převážně z oxidů železa, dále z malého množství oxidů mědi a konečně z metalických stop mědi a cínu. Prstenec byl nejspíše vykován z nízkouhlíkové oceli (resp. železa) a v žádném případě nebyl vyroben ani z šedé ani z bílé litiny.

Kovářské řemeslo Dáků *(Ľ. Mihok, V. G. Kotigoroshko)*
Stať představuje výsledky chemické a mikroskopické analýzy strusky a metalografické analýzy čtyř železných mečů pocházejících z archeologického výzkumu dáckého hradiště Malaja Kopanja, datovaného do let 60 př. n.l. až 100 n.l. Nálezy jsou výsledkem probíhajícího dlouhodobého archeologického výzkumu realizovaného Užhorodskou národní univerzitou. Výzkum ukázal, že analyzované vzorky strusky jsou jak z hutnického tak kovářského výrobního procesu. Na základě metalografické analýzy lze konstatovat, že všechny čtyři meče jsou jiného konstrukčního schématu a jakosti – zastoupeny jsou zbraně běžné i výborné. Proč byly tyto meče, nalezené v jednom komplexu poblíž hradiště Malaja Kopanja, vyrobeny v různých konstrukčních systémech je otázkou, jejíž zodpovězení vyžaduje provedení analýz více mečů i jiných železných předmětů z této lokality.

Výroba raně středověkých nožů v Británii; porovnání mezi venkovskými a městskými sídly 5. až 10. století *(E. Blakelock, G. McDonnell)*
Železné nože patří na raně středověkých lokalitách mezi frekventované nálezy, poskytující archeometalurgům dobrou příležitost pro výzkum výrobních postupů, užívaných materiálů, dovedností kovářů a odtud celkového hospodaření železem. Předchozím studiem britských raně středověkých nožů (5. až 10. stol.) byly zjištěny některé zřetelné výrobní rozdíly mezi nálezy z městských sídel a venkovských pohřebišť. Stať v této knize porovnává nože pocházející z venkovských a městských sídlišť; dva soubory nožů z venkovských lokalit Wharram Percy a Burdale byly analyzovány a porovnány se soudobými noži z měst Hamwic a York. Studie ukázala, že

mezi noži z jednotlivých lokalit nebyly zjištěny žádné konstrukční rozdíly; přesto byly rozpoznány určité odlišnosti - nejzávažnější je zjištění menšího zastoupení tepelně zpracovaných nožových čepelí na venkovských sídlech.

Metalografie nožů ze středověké vesnice Hrdlovka a pohřebiště Zlončice, Čechy *(J. Hošek, P. Meduna)*
V rámci systemizace popisu středověkých, resp. raně středověkých lokalit představují sledované lokality Hrdlovka a Zlončice dva protipóly – první je osada, druhá pohřebiště. Společným prvkem je jejich topografie (obě jsou součástí venkovského systému osídlení, bez bezprostřední prostorové vazby na opevněná sídliště), i jejich „obyčejnost“ (tedy to, že se v různých rovinách detailu neliší od srovnatelných sídlišť či pohřebišť daného období v Čechách). Realizovaný metalografický průzkum nožových čepelí rozpoznal na obou lokalitách jak čepele běžné, tak i jejich luxusnější varianty (čepele pásované, vlnkovité a jednu čepel damaskovanou). Tamní výskyt nožů je tak jednou z indicií jež nasvědčuje, že standardní dělení „hradiště = honosné“ a „venkov = druhořadé“ apod. je nedostatečné.

Technologické tradice v kovářském řemesle staroruských Šestovic *(G.A. Voznesenskaya)*
Technická vyspělost slovanského a staroruského kovářství jihovýchodní Evropy povstala na základě odkazu železářství skytského, ovlivněného technologiemi keltskými, což bylo patrné především v pozdně římském období. Ze středověké osady Šestovice u Černigova bylo podrobeno metalografickému výzkumu mnoho železných předmětů. Šlo o osadu obchodního a řemeslného charakteru, jak dokazují četné nálezy nástrojů, hotových výrobků a odpadů hutní výroby. Kovářská a keramická výroba jsou patrny ve všech částech areálu. Mezi 195 noži pocházejícími ze sídliště a pohřebních mohyl je kolem 55 % vyrobeno ve slovanské výrobní tradici a kolem 45 % bylo vyrobeno ve výrobní tradici skandinávské. Lze říci, že progresivní technologie v železářství zavedené dávnými řemeslníky se rozšířily na staré Rusi především díky vlivu skandinávské řemeslné tradice.

Další metalografický výzkum rané plátové zbroje z Churburgu *(A. Williams)*
Metalografickému šetření bylo podrobeno třináct částí plátových zbrojí, pocházejících z pěti kompletů vyrobených koncem 14. a počátkem 15. století v Miláně, dnes uložených na hradě Churburg. U exemplářů z přelomu 14. a 15. stol. byla jedna část zbroje úspěšně tvrzena kalením, nárůst tvrdosti u dalších tří souvisí s pokusy o tepelné zpracování. Všech pět analyzovaných částí zbrojí z poloviny 15. století bylo tvrzeno kalením, z

toho čtyři na tvrdost cca 300 až 400 jednotek Vickerse.

Od Soissons k Beauvais: použití železa v některých francouzských katedrálách *(P. Dillmann)*
Ze železných výztuh tří francouzských katedrál (Beauvais, Amiens a Soissons) z provincie Pikardy byly odebrány materiálové vzorky, analyzované jednak klasickou metalografickou metodou, jednak metodou analýzy struskových vměstků přednastavenou na rozlišení výrobních železářských procesů a homogenních skupin. Výsledky umožnily náhradu železných výztuh v jejich historickém a technologickém kontextu, který se u jednotlivých památek různí.

3) Příklady zapojení archeometalurgie do archeologického, historického a historicko-technologického bádání

"Archeologická" metalografie v Rusku: historiografické poznámky *(V.I. Zavyalov)*
Metalografie je již více než 60 let aktivním nástrojem studia prehistorických a historických kovových předmětů. Hlavní principy užití metalografických metod pro systematický výzkum archeologického materiálu byly formulovány B. A. Kolčinem a dále rozvíjeny dalšími průkopníky oboru, významně pak R. Pleinerem. Ve stati jsou analyzovány jednak hlavní etapy vývoje „archeologické" metalografie, jednak některé úspěchy ruské vědy na poli studia dávného kovářství. Seznam publikací věnovaných východoevropskému železářství čítá více jak 500 titulů. Většina těchto prací se věnuje slovanskému anebo staroruskému kovářství. Významná část prací se týká rovněž další závažné problematiky – počátků metalurgie železa a zpracování kovů ve východní Evropě.

Role archeometalurgie při řešení historicko-kulturních otázek *(V.I. Zavyalov, L.S. Rozanova, N.N. Terekhova)*
Archeometalurgie dnes zaujímá významné postavení v rámci metod studia archeologických předmětů. První, kdo využil metalografických metod pro studium rozsáhlých souborů archeologických předmětů byl na přelomu čtyřicátých a padesátých let 20. století B. A. Kolčin. Skupina archeometalurgů sestávající z autorů této statě (někdejších Kolčinových žáků) nyní aktivně působí v Archeologickém ústavu RAS v Moskvě jako složka Laboratoře přírodovědných metod výzkumu, která disponuje rozsáhlou arche-

ometalografickou databází, čítající k dnešnímu dni více než 11000 vzorků shromážděných z různých historických období a geografických oblastí. Na konci osmdesátých let minulého století vyvstal jako nejaktuálnější problém celková klasifikace, generalizace a konceptualizace obrovského množství nesourodých dat, vážících se k východoevropské železářské technice a technologii sledovatelné od nejranějšího období až po středověk. Práce na tomto úkolu byla završena knihou „Kapitoly z dějin starého východoevropského železářství (Essays on the history of ancient iron working in Eastern Europe)".

Později se badatelské úsilí autorů zaměřilo na sledování otázky „Tradice a novátorství ve výrobě starověkých národů (například tradice a novátorství v kovářském řemesle)". Obzvláštní pozornost byla věnována otázce utváření tradic kovářského řemesla mezi národy ugrofinskými z oblastí Volhy a západního Uralu. V dějinném vývoji ugrofinského kovářského řemesla vidíme brzký (8. až 6. stol. př.n.l.) a náhlý výskyt železných předmětů vyspělého tvaru v oblasti střední Volhy. V kovářském řemesle volžských a západouralských ugrofinských národů 9. století vidíme dramatický pokrok, související se zapojením těchto národů do trans-evropského obchodního systému pomocí Volžsko-baltské obchodní magistrály.

Jinou významnou částí projektu je problém vývoje výrobní tradice ve staroruském kovářském řemesle. Získané výsledky dovolují konstatovat, že tradice předmongolského období přetrvaly ve staroruském kovářství i za Zlaté hordy.

Předložené materiály představují nejzávažnější sporné otázky v dějinách východoevropského kovářského řemesla; na základě archeometalografických dat mohly být rozřešeny v rovině historicko-technologické, ale mají i obecnou historickou platnost.

Interdisciplinární výzkum (archeologie a archeometrie) kovářského zpracování produktů přímé výroby železa ve Francii. Vybrané výsledky posledních dvou dekád výzkumu *(P. Fluzin, S. Bauvais, M. Berranger, G. Pagès, P. Dillmann)*

Archeometrický a archeologický výzkum prováděný ve Francii v průběhu posledních dvaceti let umožnil definovat různé fáze výroby (Chaîne opératoire) železa a oceli, jakož i ukazatele s nimi spojenými (archeologické struktury, odpady). Tyto studie ukazují, že jednotlivé výrobní fáze mohou (nebo nemusí) být rozděleny v prostoru i čase, a mohou mít i různý stupeň intenzity (malo-, velkovýroba). To znamená, že výrobní místa mohou být různé povahy: mohla zajišťovat pouze dílčí výrobní operace stejně jako kompletní výrobu. Rovněž to znamená, že jsou součástí sociálního kontextu (např. venkovského, městského, specializovaného nebo obecného řemesla). Vzájemné vztahy mezi výrobními fázemi vytvářejí vazby mezi jed-

notlivými lokalitami a prostřednictvím obchodu s polotovary a hotovými výrobky vytvářejí technologický, ekonomický a sociální systém. Aby se dosáhlo uceleného pochopení této organizační struktury, musí být vývoj daného systému studován s přihlédnutím ke kulturnímu a politickému kontextu toho kterého období. Určení výrobní aktivity (tavení, zkujňování, zpracování, spotřeba, recyklace), stejně jako její intenzity, umožňují realizaci dynamického – synchronního i diachronního – zmapování těchto aktivit. Fyzikálně-chemické vazby mezi rudou, hutnickou struskou, posthutnickou struskou a vyrobeným kovem, umožňují pochopit vazby mezi lokalitami, které jsou součástí stejného směnného systému. To odráží regionální rozvoj organizace hutnictví a obchodu železnými polotovary a hotovými výrobky. Typologické vlastnosti (morfologie, míra znečištění vměstky, obsah uhlíku a fosforu. . .) polotovarů ze zpracovatelských lokalit rovněž umožňují upřesnit naší představu o tom co bylo v oběhu a co dané lokality nabývaly. Archeologické a historické studium těchto údajů tak může formovat naší relativní představu, kterou máme o těchto vazbách v různých obdobích.

4) Příklady experimentu v archeometalurgii

Surové železo z pece na přímou výrobu železa *(P. Crew, M. Charlton, P. Dillmann, P. Fluzin, C. Salter, E. Truffaut)*
V rámci badatelského programu provázaného s archeologickým výzkumem železářské dílny 14. století v Llwyn Du (Severní Vels) byla v Plas Tan y Bwlch provedena série experimentů s tavením vysoko manganových bahenních rud. Při experimentu č. 92 bylo dmýcháno dvěma velkými ručními měchy, poskytujícími daleko větší podíl vzduchu na podíl spáleného dřevěného uhlí, než který je obvyklý pro malé pece pro přímou výrobu železa. Produktem tavby byl blok surového železa, který se zformoval v obvyklé pozici železné houby, a který byl ke stěnám pece přichycen přilnavou struskou s nízkým podílem železa. Tento nezáměrný výsledek ukazuje, že surové železo může být v určitém množství relativně snadno získáváno i v pecích pro přímou výrobu železa. Existuje tedy přirozené a zajímavé vysvětlení zvyšujícího se počtu železářských dílen (pro přímou výrobu železa) z celé Evropy, ve kterých bylo nalezeno jak surové železo tak vysokouhlíková ocel.

***The Celtic Sword:* zdroj praktické inspirace** *(J. Lang)*
Práce R. Pleinera *The Celtic Sword* (1993) byla částečně inspirací k prove-

dení série experimentů, realizovaných v rámci výzkumu mechanických vlastností starověkých mečů. Rozdílnost v uplatňovaných konstrukcích mohla být částečně jen estetická, praktické důvody však patrně hrály svou roli rovněž. Stať podává přehled výsledků série mechanických zkoušek provedených na moderních železných/ocelových tyčích vykovaných v různých konfiguracích dle zadání autorky. Nakonec jsou stručně diskutovány získané závěry a meze celého výzkumu.

The Editors

PLATES

Plate I

Figure 1: Radomír Pleiner (right) at the beginning of his career, with Boris Kolchin during smelting experiments in Russia, around 1962. Photo: Archive of Institute of Archaeology RAS Moscow (provided by V. Zavyalov).

Plate II

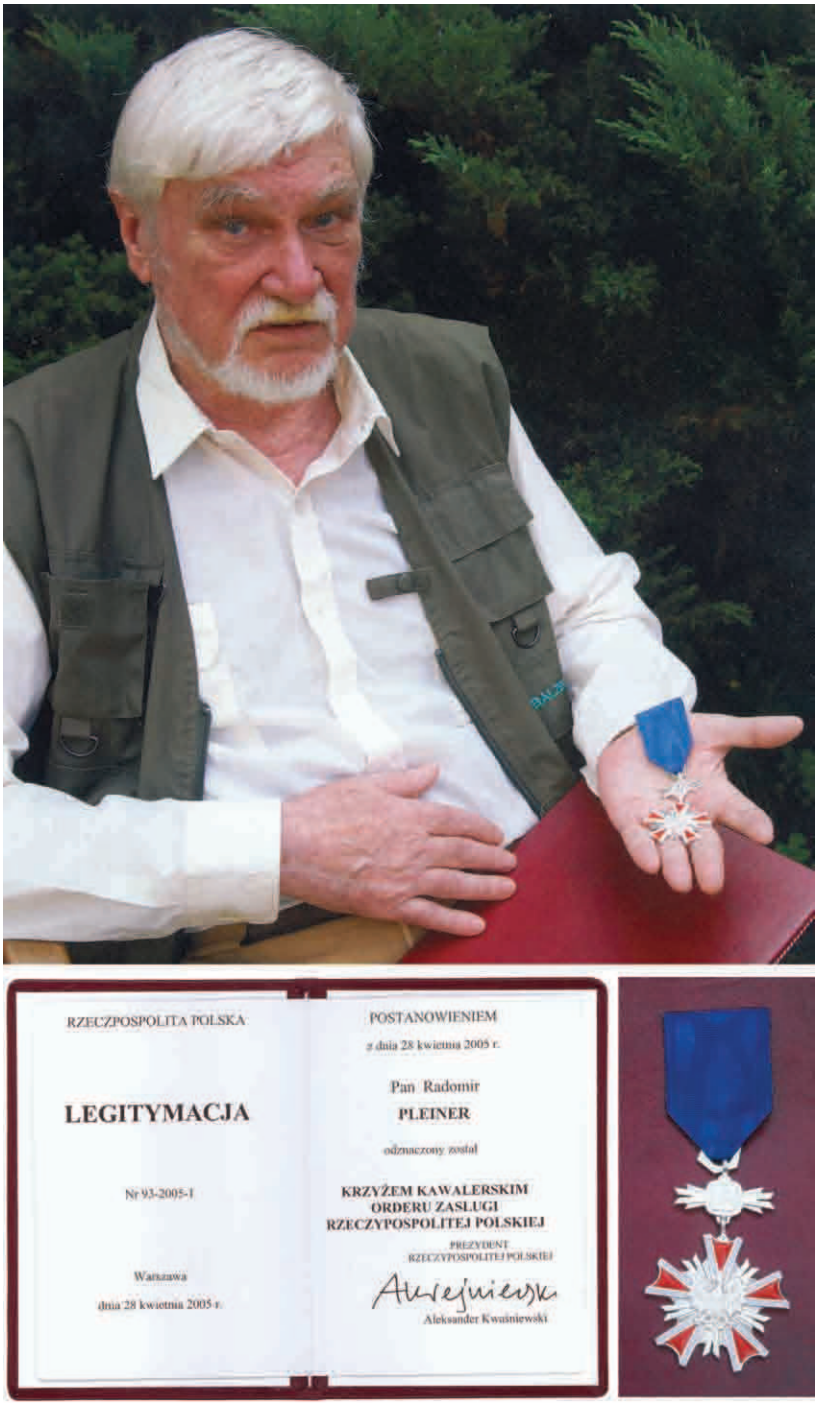

Figure 2: Radomír Pleiner and the Knight's Cross of Merit of the Republic of Poland. Photo from the Pleiner family archive.

Plate III

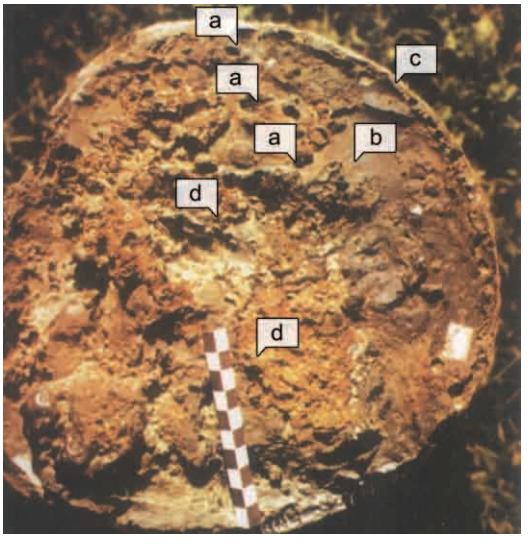

Figure 4: Kowalkowice (Świętokrzyskie Mountains). The upper part of the slag block with the characteristic surface of solidification: a: traces of the bursting gas bubbles; b: the surface wrinkle; c: casting shrinkage at the edge; d: elements of the clay and a larger piece of the wall of the shaft removed after the smelt. Photograph by K. Bielenin.

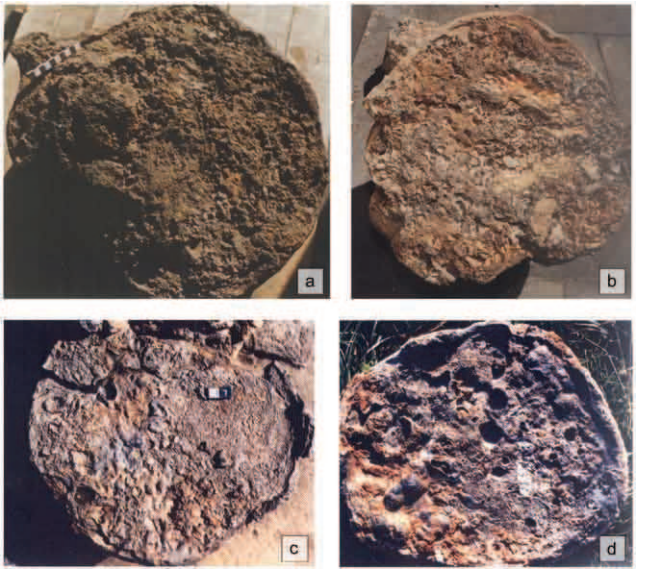

Figure 6: Examples of different appearances of the surface of the unimpeded slag solidification (average block diameter approx. 45cm, weight 80–100kg: a: Wronów (Świętokrzyskie Mountains), photograph by K. Bielenin; b: Rudki (Świętokrzyskie Mountain), photograph by R. Łapanowski; c: Brwinów (Masovia); d: Młochów (Masovia). Photographs by S. Woyda

Plate IV

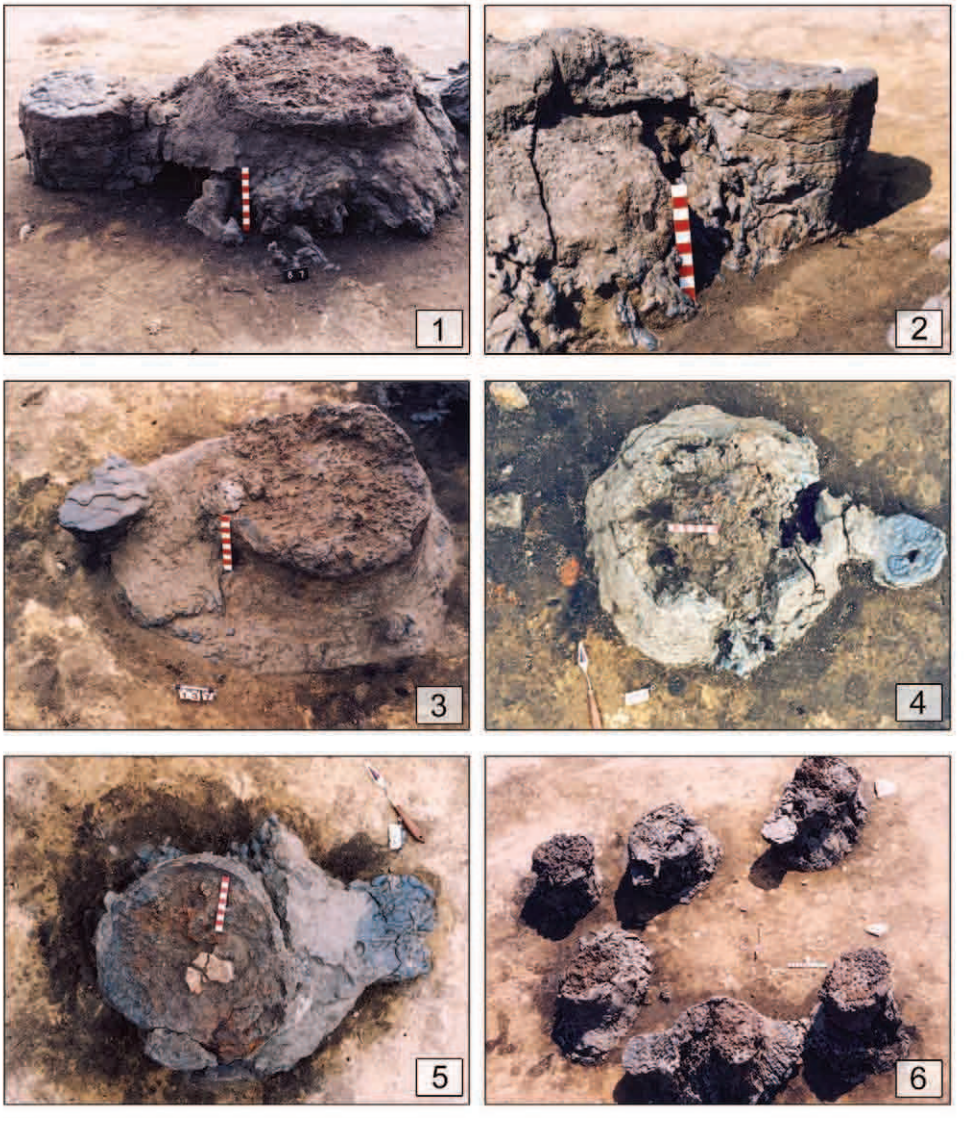

Figure 8: Selected examples of furnaces with canal-pits from Mazovia, Brwinów (1-6). Photograph by S. Woyda.

Plate V

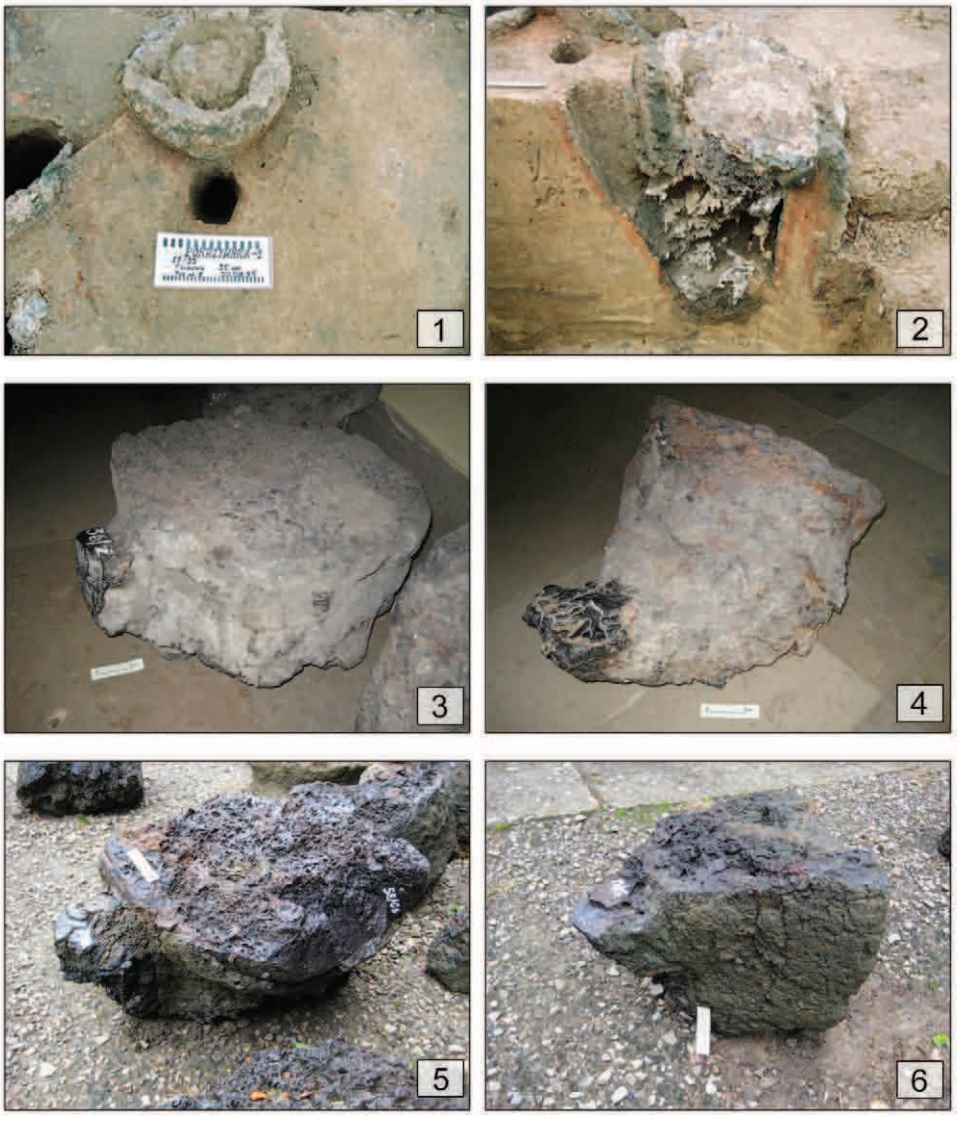

Figure 12: Selected samples of furnaces with canal-pits from the Świetokrzyskie Mountains: Pokrzywnica (1-2), Skarżysko-Kamienna (4), Tarczek (3), and Garbacz Skała (5-6) sites. Photographs by S. Orzechowski.

Plate VI

Figure 14: Skovmark, Aistrup parish, Aalborg county. Vertical photograph of the bottom of the furnace.

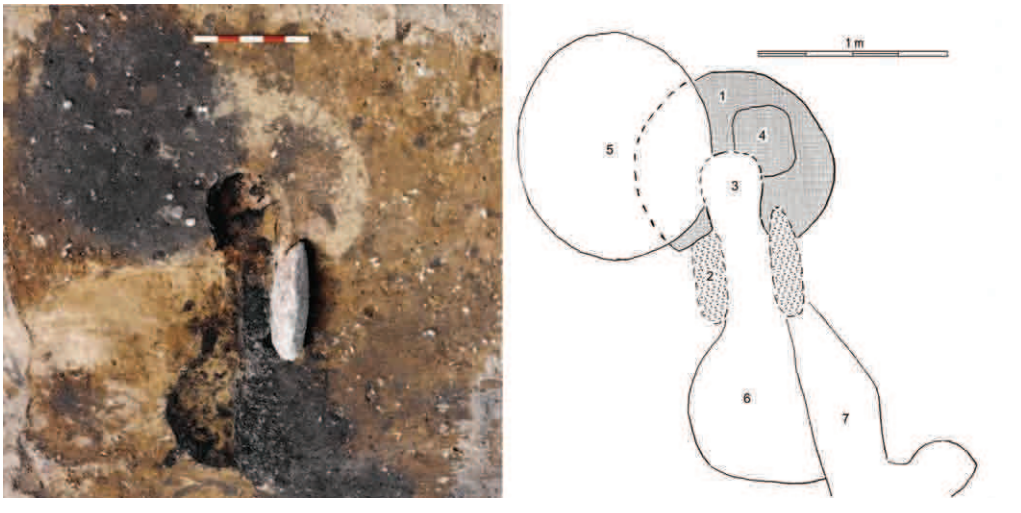

Figure 15: Sønder Holsted, Holsted parish, Ribe county: Vertical photo of furnace A105, partly excavated; plan of furnace A105 – 1: The clay packing, 2: Flagstones, 3: Slag drain, 4: Secondary disturbance, 5 The secondary pit, 6 The working pit, 7 Secondary disturbance. Scale 50cm.

Plate VII

Figure 16: Sønder Holsted, Holsted parish, Ribe county: Furnace A187 after excavation. Scale 50cm.

Figure 19: Espe, West Sealand. Inner side of clay tuyère plate.

Plate VIII

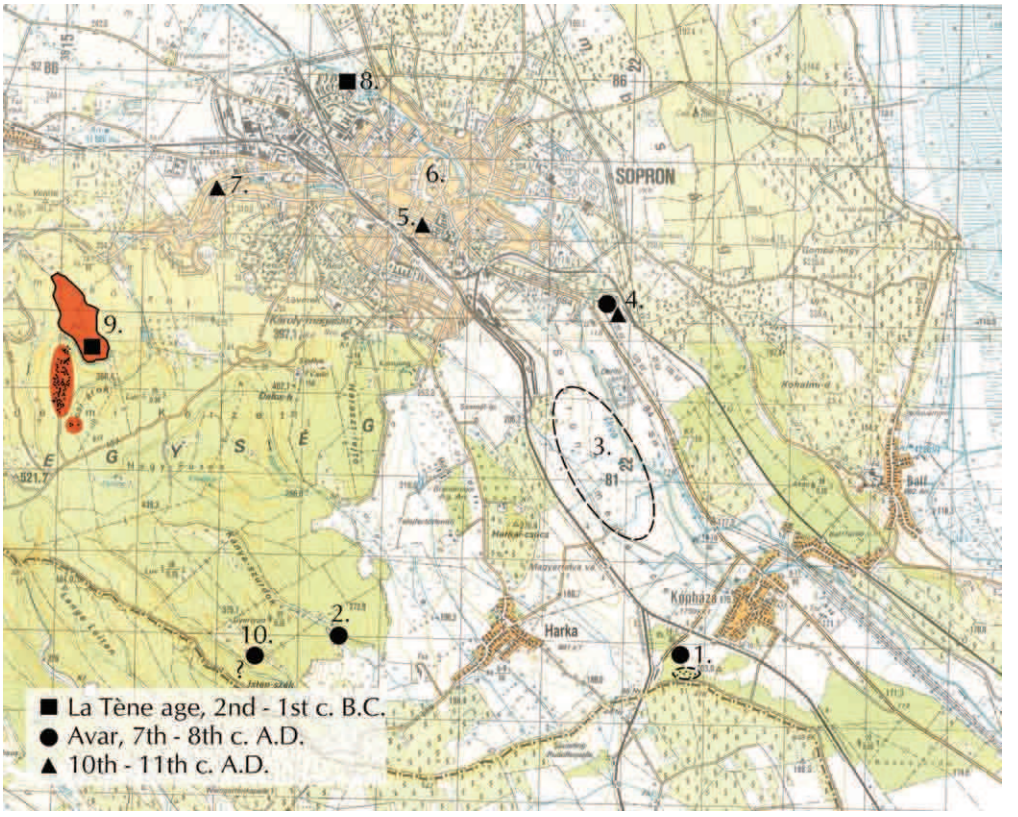

Figure 23: Iron production sites near Sopron. 1: Kópháza, minepit field (Avar? - Medieval) and a metallurgical furnace (J. Gömöri 1999); 2: Harka–Kányaszordok (Bikarét), free-standing furnaces built of stone (Avar) (J. Gömöri 2000); 3: *terra Koachi... que fuit fabrorum castri Supruniensis* (1268); 4: Potzmann dűlő (balk), Avar and 10th century furnaces, ore-roasting pits (J. Gömöri 1999); 5: Deák tér (square), 11th century bloomery workshops (M. Radnóti, Gy. Nováki 1968, G. Gabrieli); 6. The fortified Scarbantia (4th century) and the Árpád age castrum Supron (late 10th century–1277), the medieval inner town (J. Gömöri 2002); 7: Bánfalvi út, 10th–11th century bloomery and dwelling house (J. Gömöri 1973); 8: Krautacker, Celtic settlement with an 'industrial quarter,' an iron-reheating furnace and some pottery kilns (J. Gömöri 2002, E. Jerem); 9: Sopron–Burgstall, Hallstatt period, and late La Tène age hillfort, sporadic iron slags (E. Patek); 10: Magas-híd, slag heaps with early medieval tuyère panels made of clay (Gy. Nováki 1958). (Base map: M. Honv. Térk. Hiv.1: 25000, Sopron-Nekenmart, reduced detail. Constructed by J. Gömöri 2009)

Plate IX

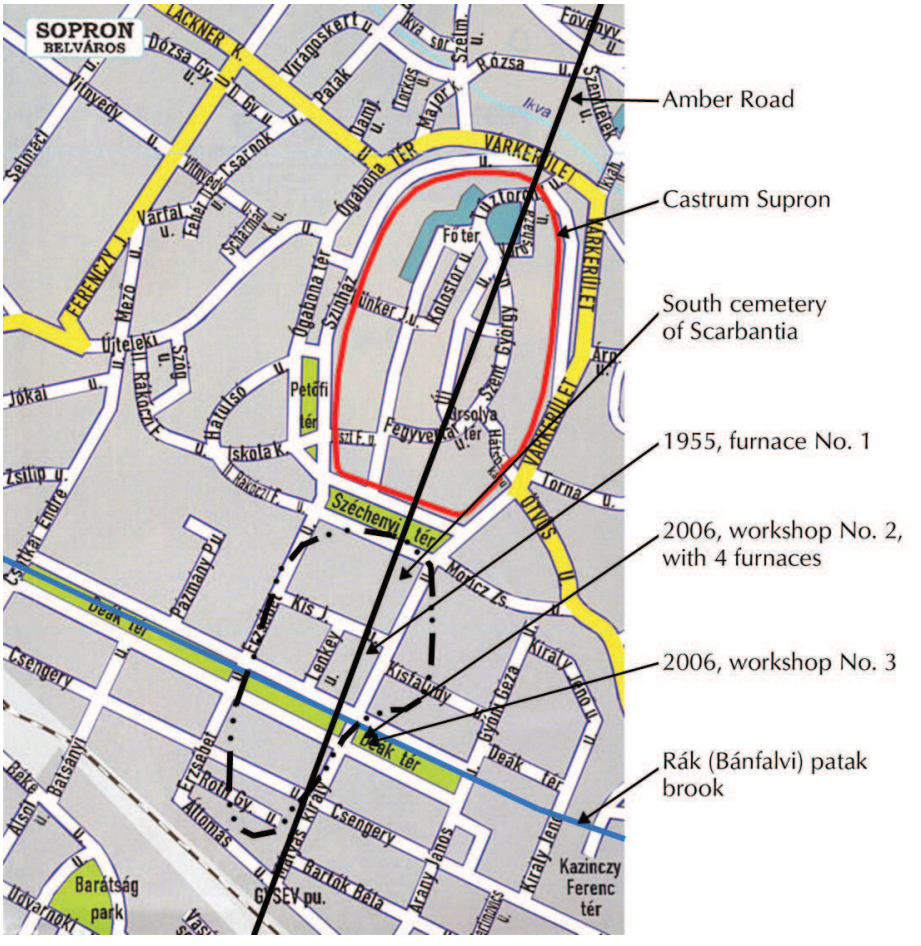

Figure 24: The location of the workshops near the brook, south of the *castrum* with red burnt rampart behind the Roman period stone wall. (Scale: the fortification marked in red is 400m long and 250m wide. Constructed by J. Gömöri 2009).

Plate X

Figure 25: Sopron, Deák tér. Bloomery No 2 (= 2006/1 obj.) with paired, thin-walled, embanked, shaft furnaces. Broken line shows the Period I.: bottom of coupled furnaces (A1 and B1), entrance (E). Period II.: enlargement of the workshop, furnaces (A, B), ore- and charcoal-storage niche. (Photograph by G. Gabriella, interpreted by J. Gömöri).

Figure 28: A view of the area of Technical Heritage Stará huť near Adamov. Iron-smelting experiments in reconstructed early medieval furnaces take place there. Photograph by J. Merta.

Plate XI

Figure 31: Reconstruction of the original view of the Great Moravian bloomery (9th century), Olomučany, forest section 98/1, central part of the Moravian Karst. Drawing by J. Balák. After Souchopová & Stránský 2008.

Plate XII

Figure 32: Drawing from 1991 of a Roman age bloomery in Trøndelag by Inkalill, slightly revised later by the designer. Notice the cyclic operation of the four furnaces.

Figure 33: Bloom from Akset containing about 0.2% C. Weight 17.8kg. T - 21 175. Photograph by A. Espelund.

Plate XIII

Figure 35: Furnace excavated at Dokkfløy. It was built from clay and was supported by vertical slabs on three sides. Note the hole for the nozzle of a bellows and for tapping of slag in front. Photograph by M. Thorleifsen.

Figure 36: Bloom from Veum, Fyresdal, County of Telemark. Photograph by KHM.

Plate XIV

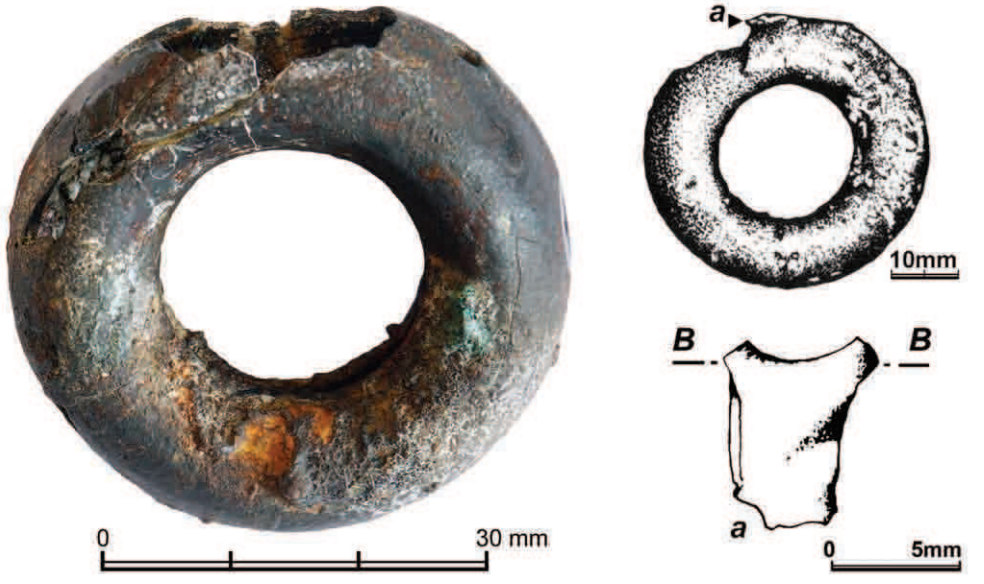

Figure 39: (Left) Photograph of the hollow ring from the Bull's Rock cave (collections of the Moravian Museum in Brno): (right) drawing showing location of (above) sample *a* taken from the ring and (below) cross-section B-B of the metallographic specimen. Photograph by I. Balák.

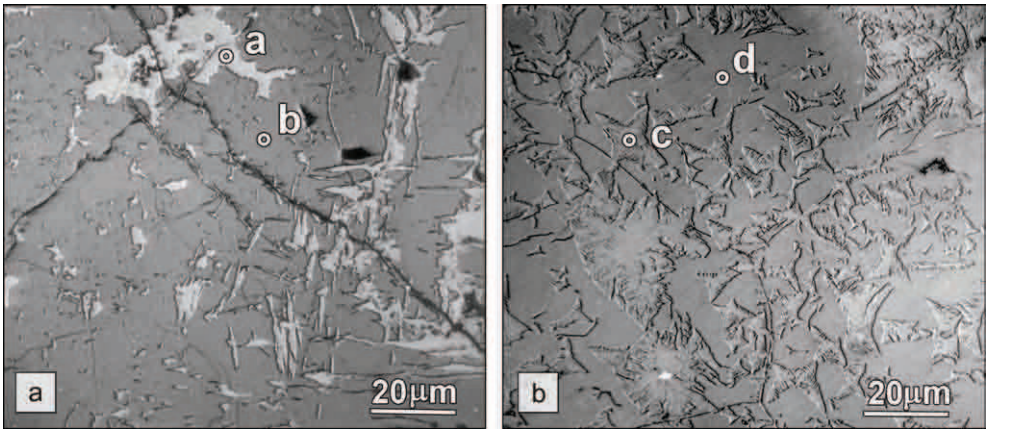

Figure 41: The microstructure of the iron ring: *left* (very near its surface) a – goethite and b – hydro-hematite; *right* (farther from the surface) c – hydrohematite in the shape of the star, and d – magnetite. Photograph by K. Stránský.

Plate XV

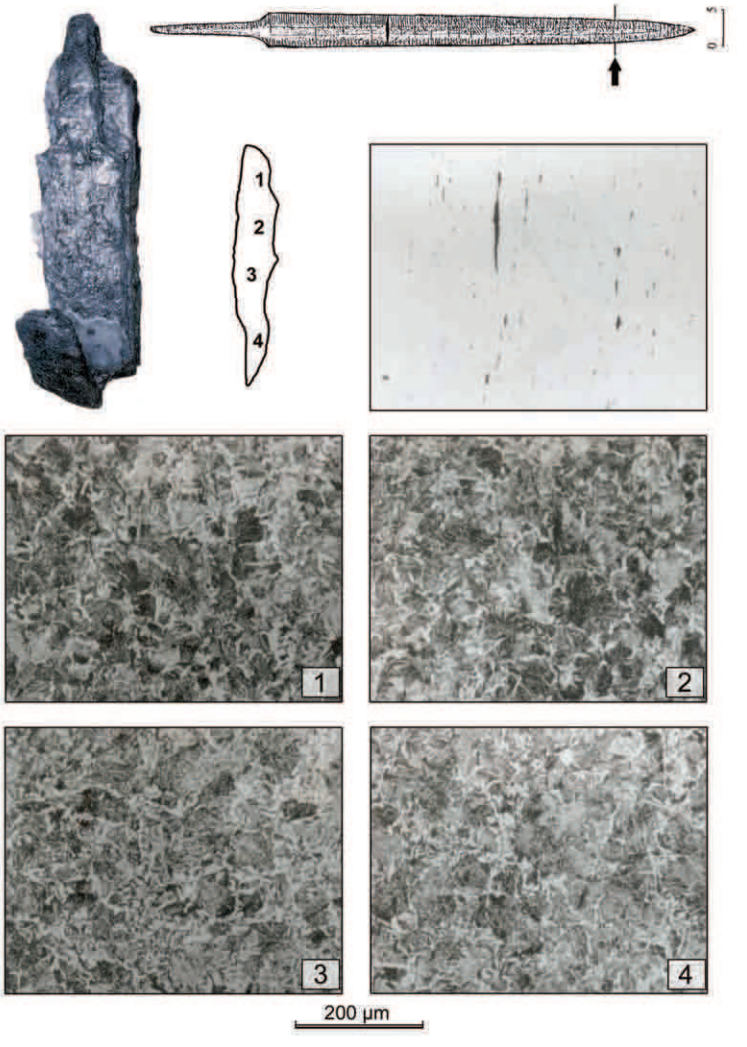

Figure 49: Metallographic analysis of sword 3. Microphotographs by Ľ. Mihok.

Plate XVI

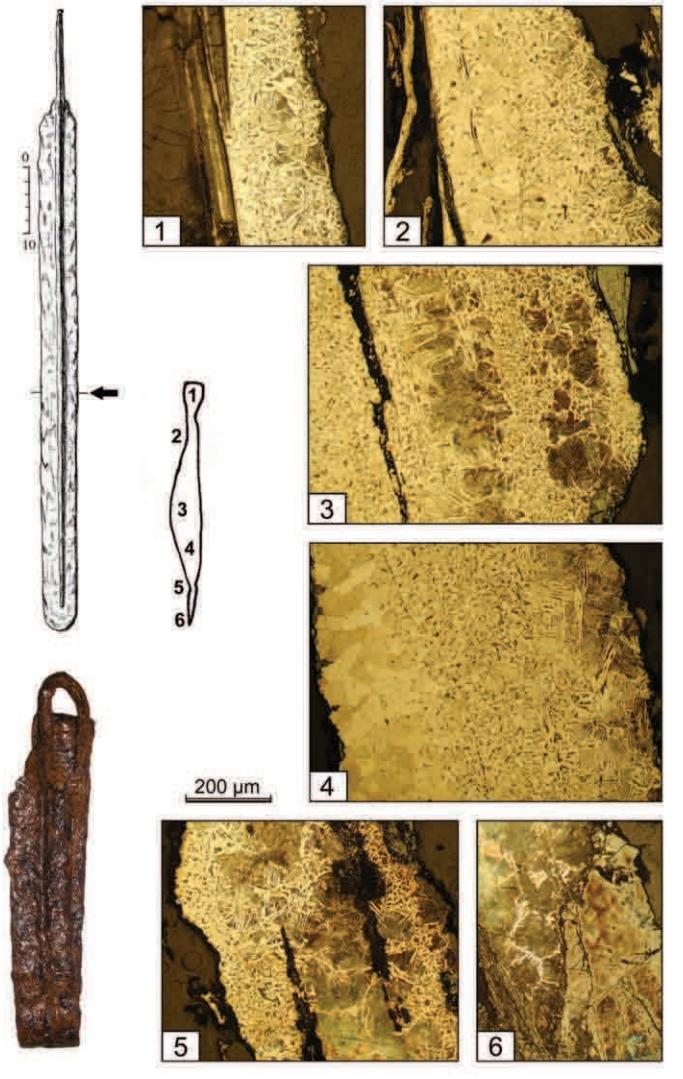

Figure 50: Metallographic analysis of sword 3. Microphotographs by Ľ. Mihok.

Plate XVII

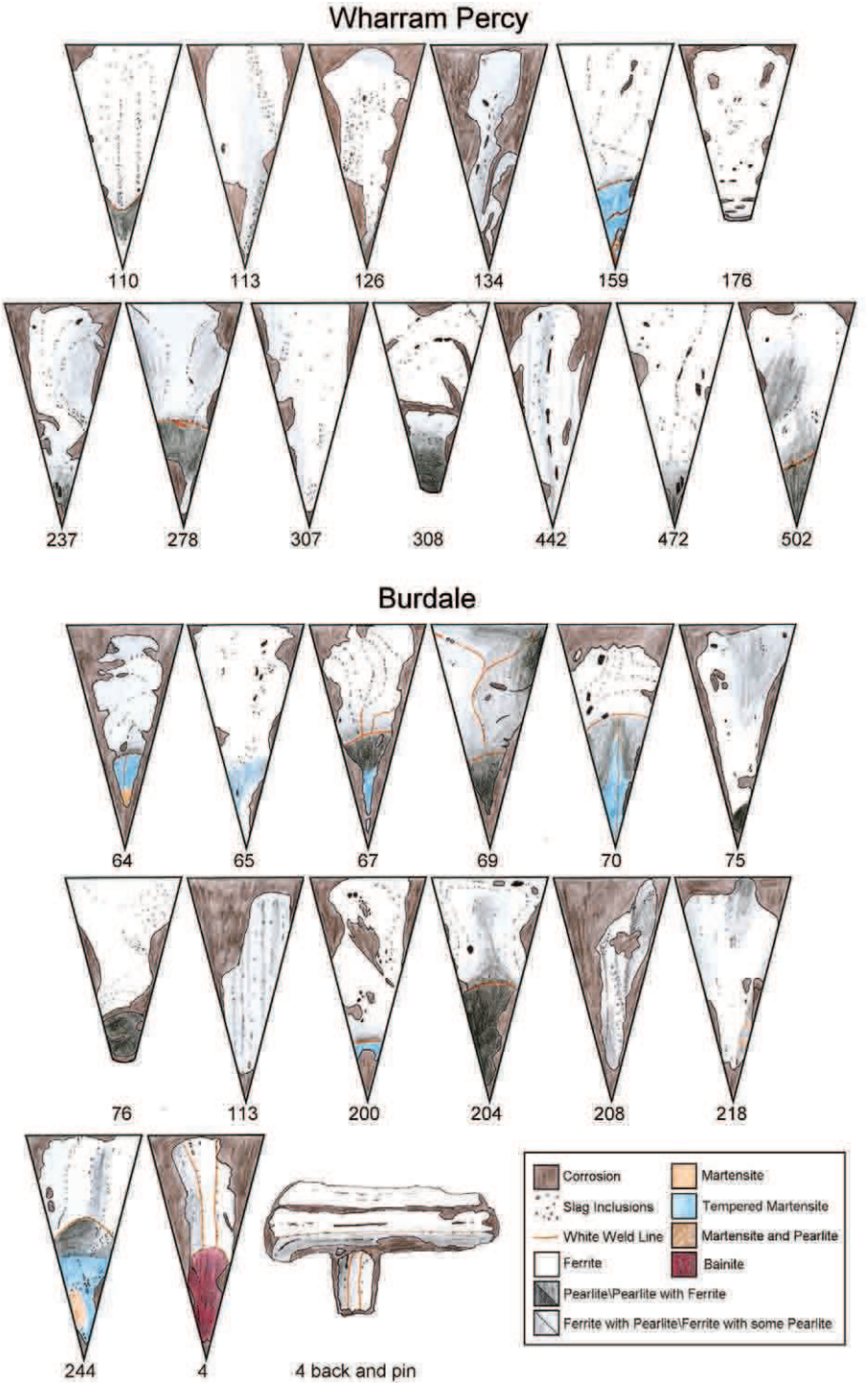

Figure 54: Sketches of the knives from Wharram Percy and Burdale. By E. Blakelock.

Plate XVIII

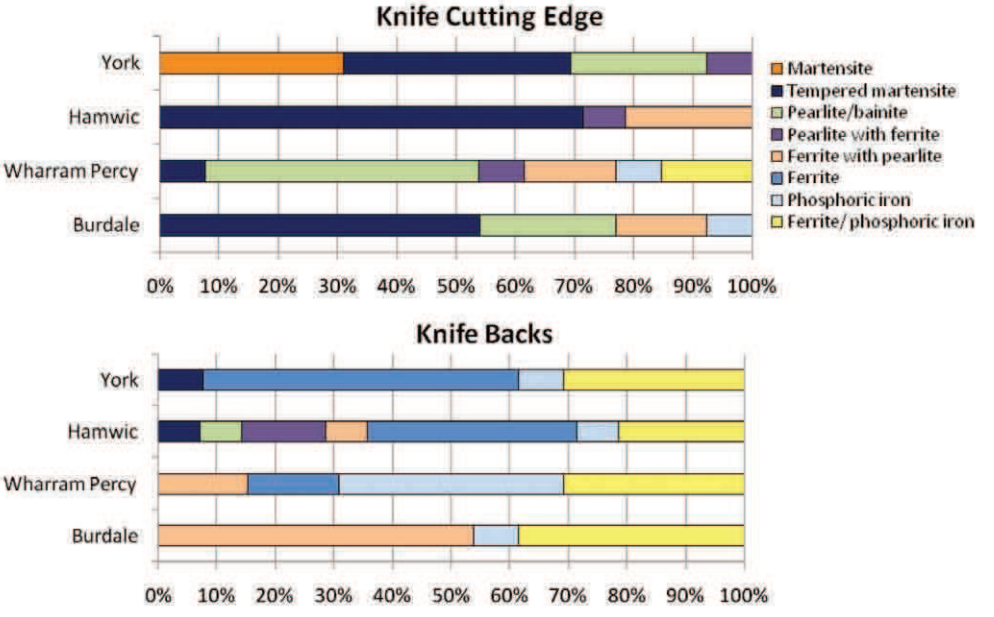

Figure 56: Bar charts showing the percentage of different microstructures and therefore alloy types present in knife cutting-edges and knife backs at each site. By E. Blakelock.

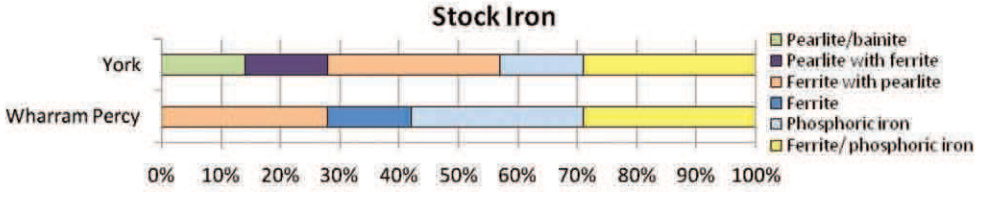

Figure 57: Bar charts showing the percentage of different microstructures and therefore alloy types present in bars found at Coppergate, York, and Wharram Percy. By E. Blakelock.

Plate XIX

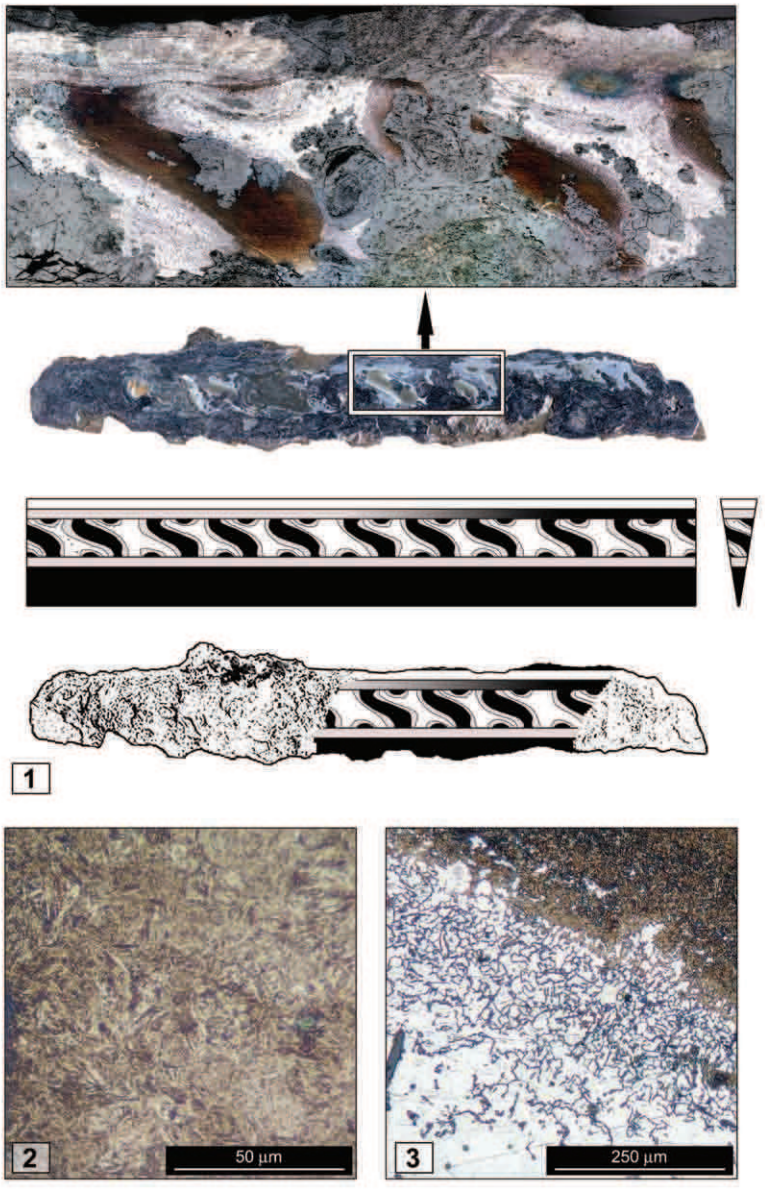

Figure 62: Zlončice, *c* 11th century; pattern-welded knife 24 (grave 25); 1: detail of the lateral polishing, which revealed a patterned core; 2: martensitic structure of the cutting-edge; 3: structures of the pattern-welding; etched with nital. Photographs by J. Hošek.

Plate XX

Figure 66: Armour (Churburg 18). Photograph by courtesy of Count Trapp.

Plate XXI

Figure 72: Armour Churburg 21 exhibited with a sallet (open helmet). Photograph by courtesy of Count Trapp.

Plate XXII

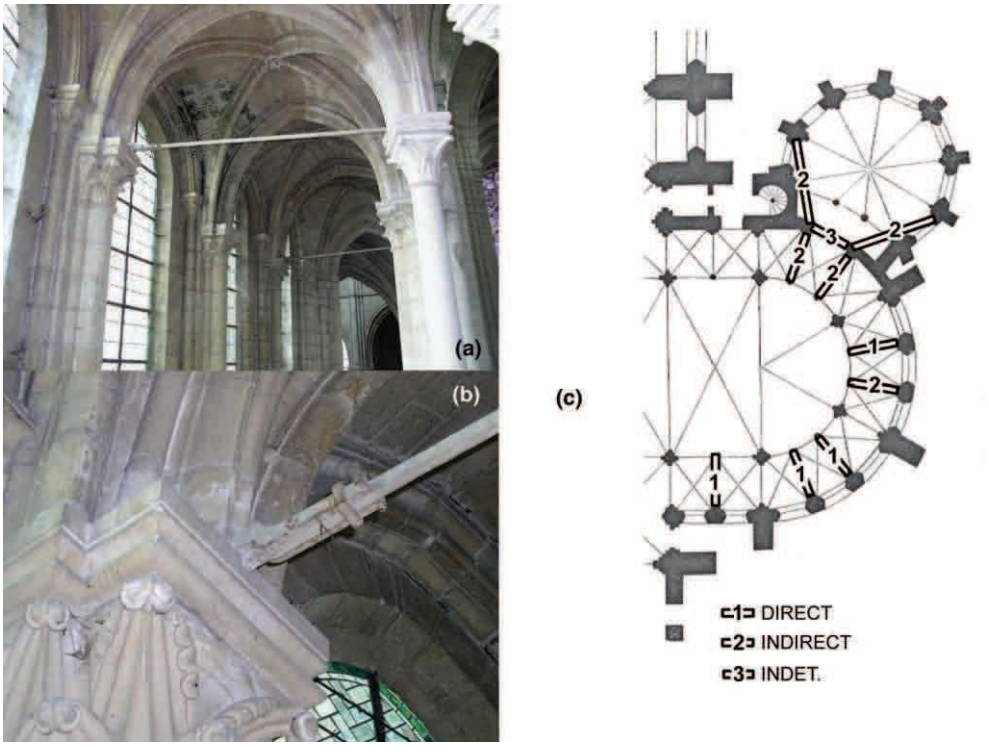

Figure 75: Soissons Cathedral. South transept (a) ferrous reinforcement in the gallery; (b) close-up view of a fastener; (c) ferrous tie-rod location and process, 1: bloomery process, 2: indirect, 3: undetermined. Original plan: Viollet-Le-Duc.

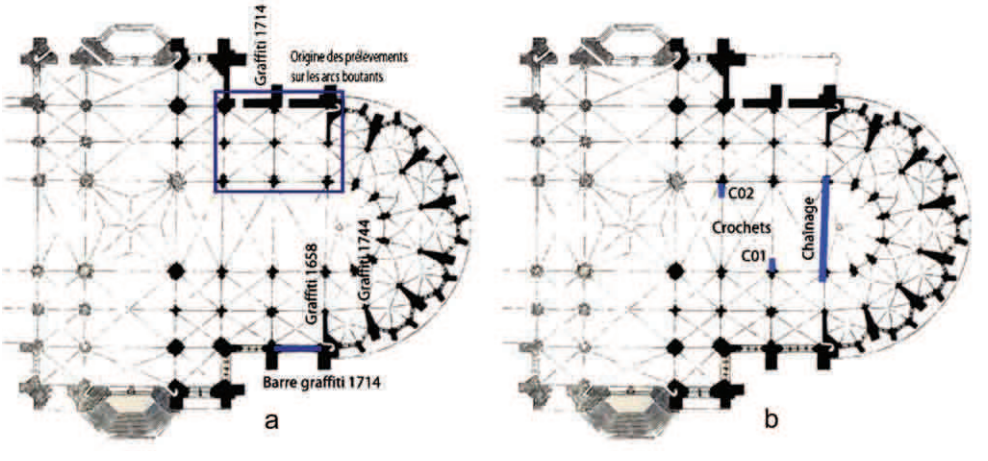

Figure 76: Sample locations in Beauvais Cathedral. (a) between the flying buttresses; (b) in the attic. Original plan: Viollet-Le-Duc.

Plate XXIII

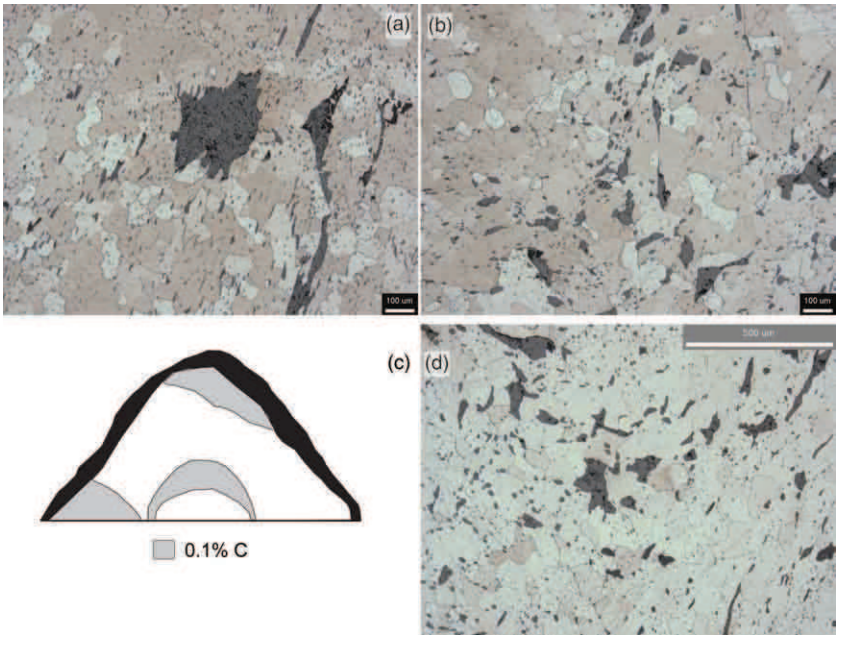

Figure 78: Microphotographs obtained on samples (a) T1E, (b) T2I, (c) T4 I – schematic of the structure and (d) TN after nital etching.

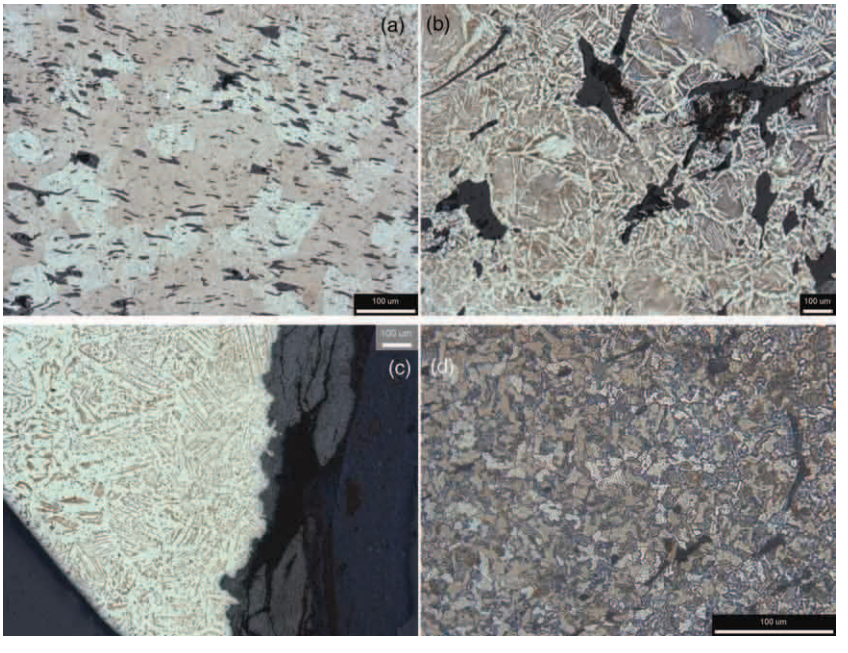

Figure 79: Microphotographs obtained on samples (a) T3 E, (b) T5 I, (c) T6 I, and (d) T6 E after nital etching.

Plate XXIV

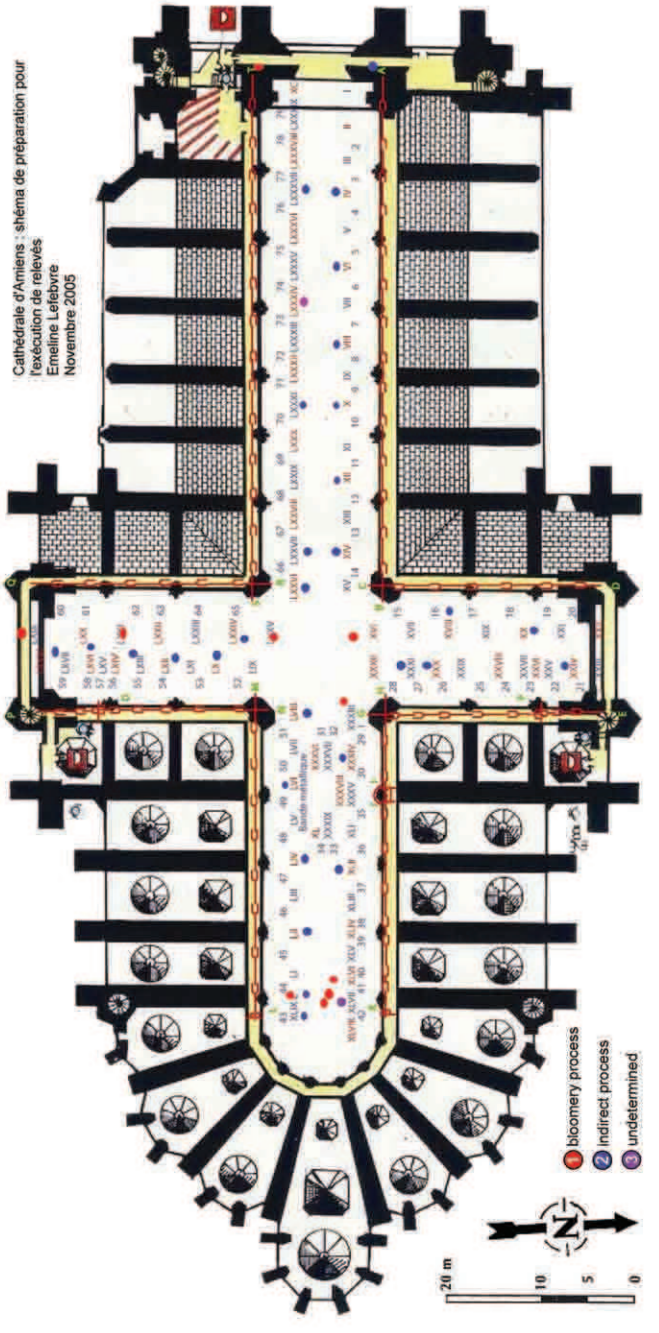

Figure 87: Position of the sampled links in the triforium of Amiens Cathedral and the ironmaking process as determined by slag-inclusion analysis 1: bloomery process. 2: indirect process, 3: undetermined.

Plate XXV

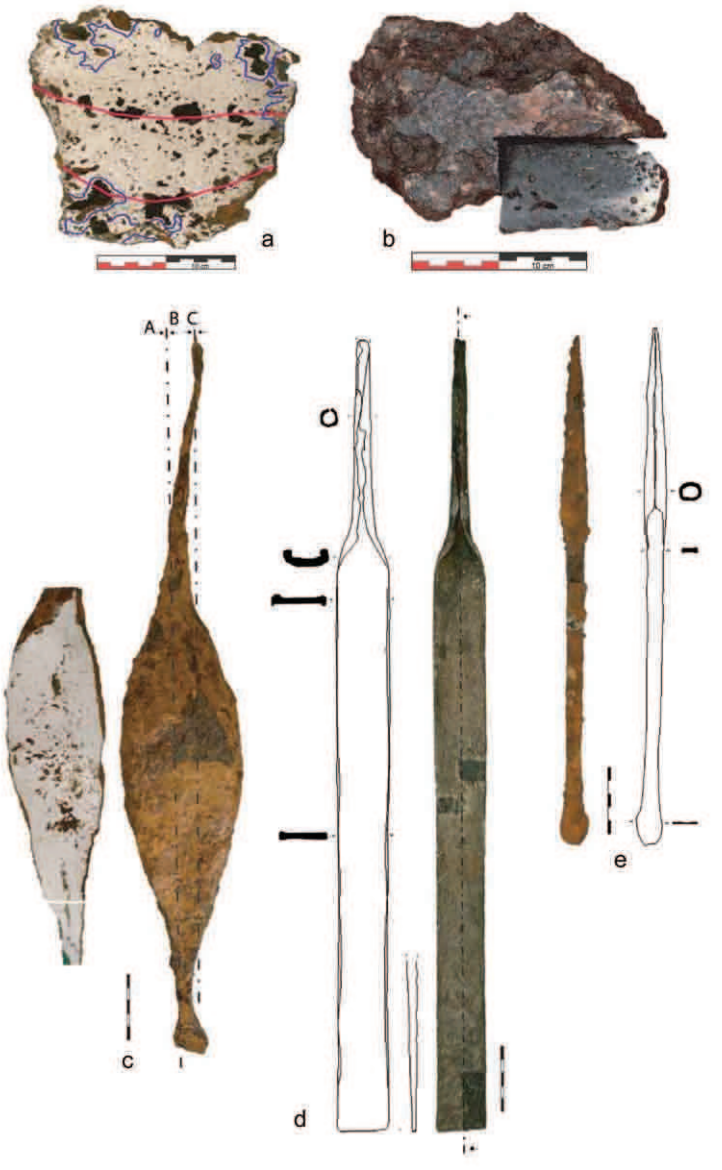

Figure 99: a: Raw bloom from Piani d'Erna (Italy); 2nd century BCE – 1st century AD; weight: 33kg and 38kg (Fluzin 2006); b: bloom from Selongey (Burgundy-France); Gallo-Roman; weight: 2.37kg.; c: iron bipyramidal bar from the hoard of Nottonville (Eure et Loir, France). 8th–5th century. BCE (14C date); NOT.94.14.07; weight 4950g; length 574mm, width 86mm, thickness 78mm.; d: iron 'currency bar' from the Saône river at Pouilly-sur-Saône (Burgundy, France) 3rd–1st century BCE; SAO.81.03.01; weight 650g; length 598mm; width 45mm; thickness 5mm.; e: iron 'socket bar' from the sanctuary of Saint-Maur (Picardie, France), 2nd century BCE; SM.5445; weight 69g; length 387mm; width 22mm; thickness 3mm. Photographs and sketches by P. Fluzin and M. Berranger.

Plate XXVI

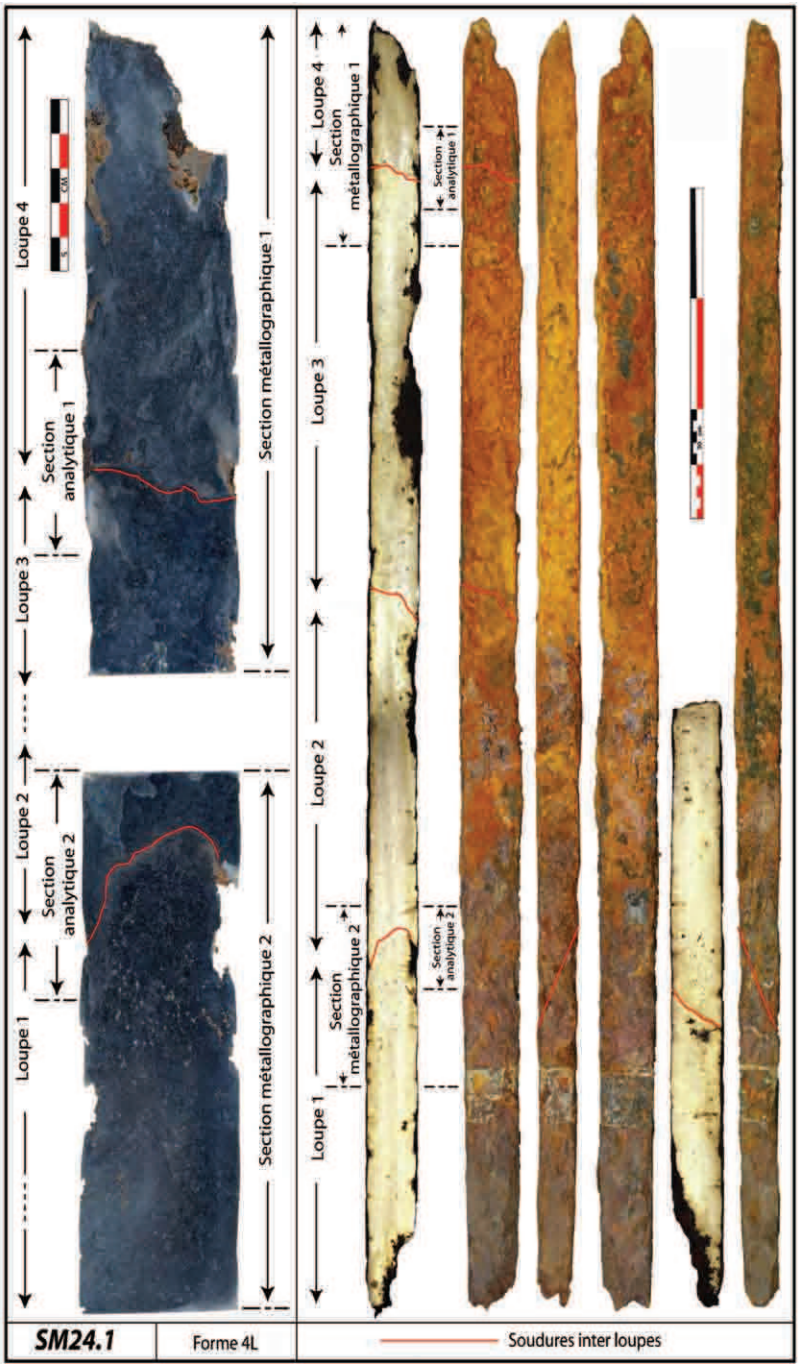

Figure 100: Bars (type 4L) discovered in the Roman wreck (SM24: 1st century BCE to 2nd century AD). Saintes-Maries-de-la-Mer (Bouches-du-Rhône, France). Weight 14kg, length 1160mm, width 58mm, thickness 40mm. Photographs and sketches by G. Pagès.

Plate XXVII

Figure 101: Top left: Batch A bog-ores, scale 10cm. Top right: The bellows and blowing hole. Bottom: General view of the experiment in progress. Photographs by P. Crew.

Plate XXVIII

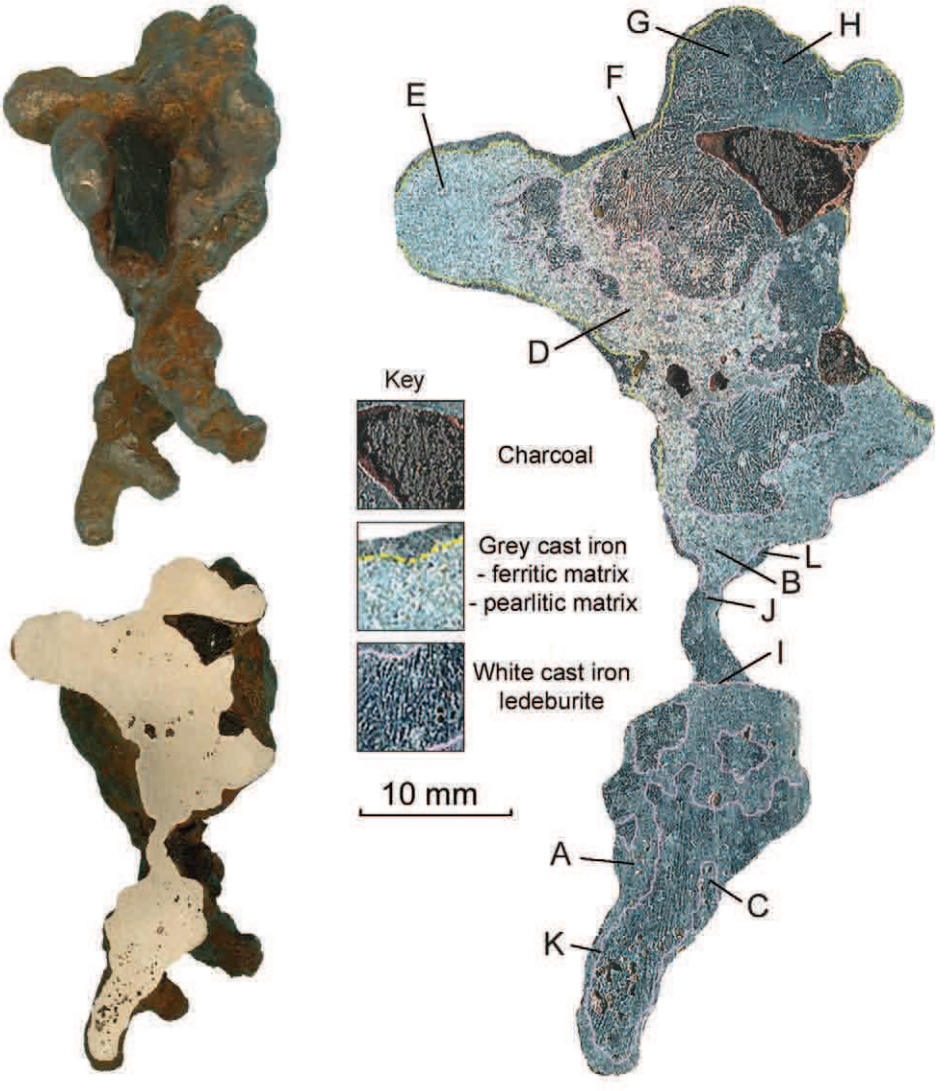

Figure 105: Left: sample B3, cut and polished (approx. 1:1). Right: Macrophotograph of etched sample, with locations of microphotographs A-L (approx. 1:2). Photographs by P. Fluzin.

Plate XXIX

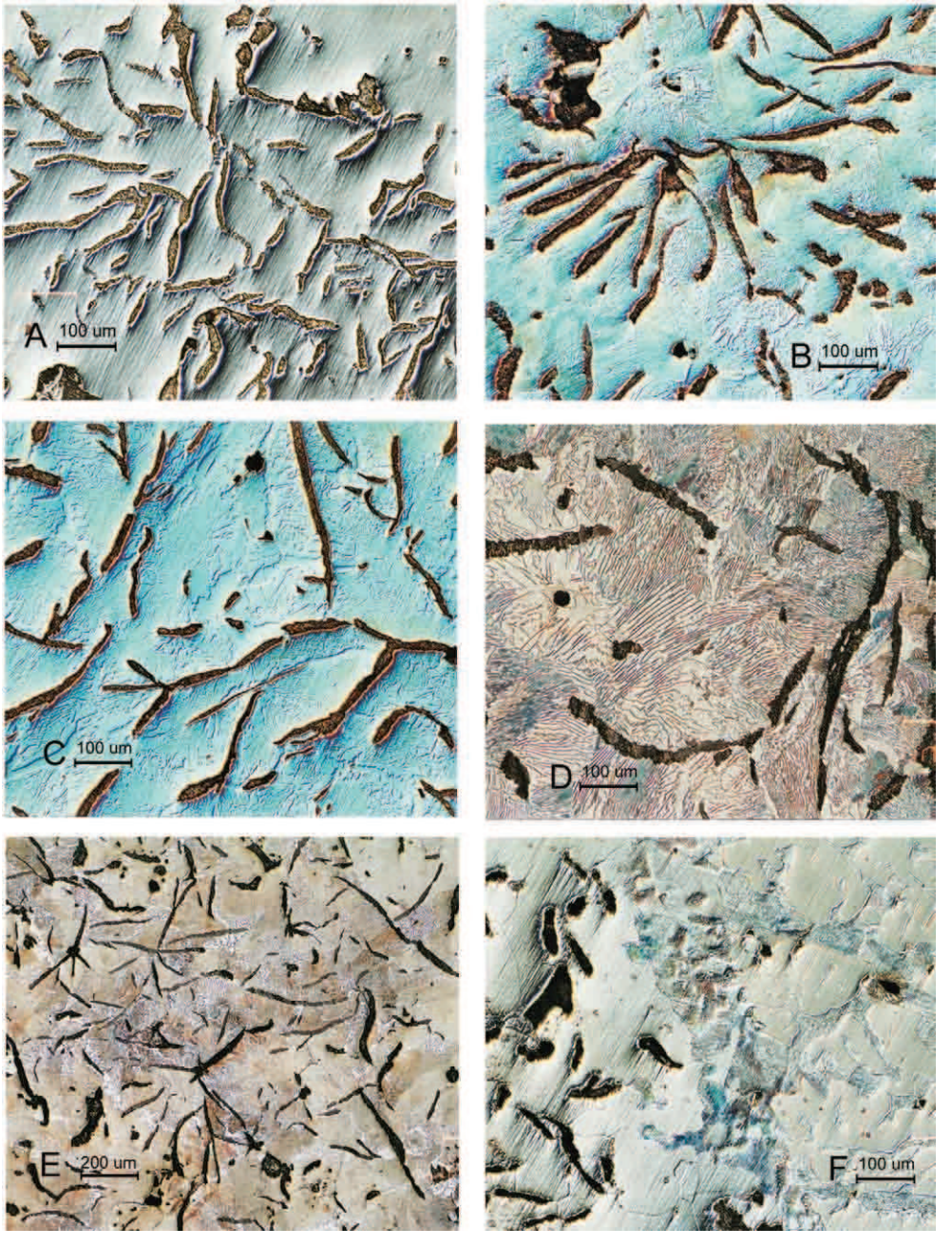

Figure 106: Microphotographs of B3 grey cast iron. Photographs by P. Fluzin.

Plate XXX

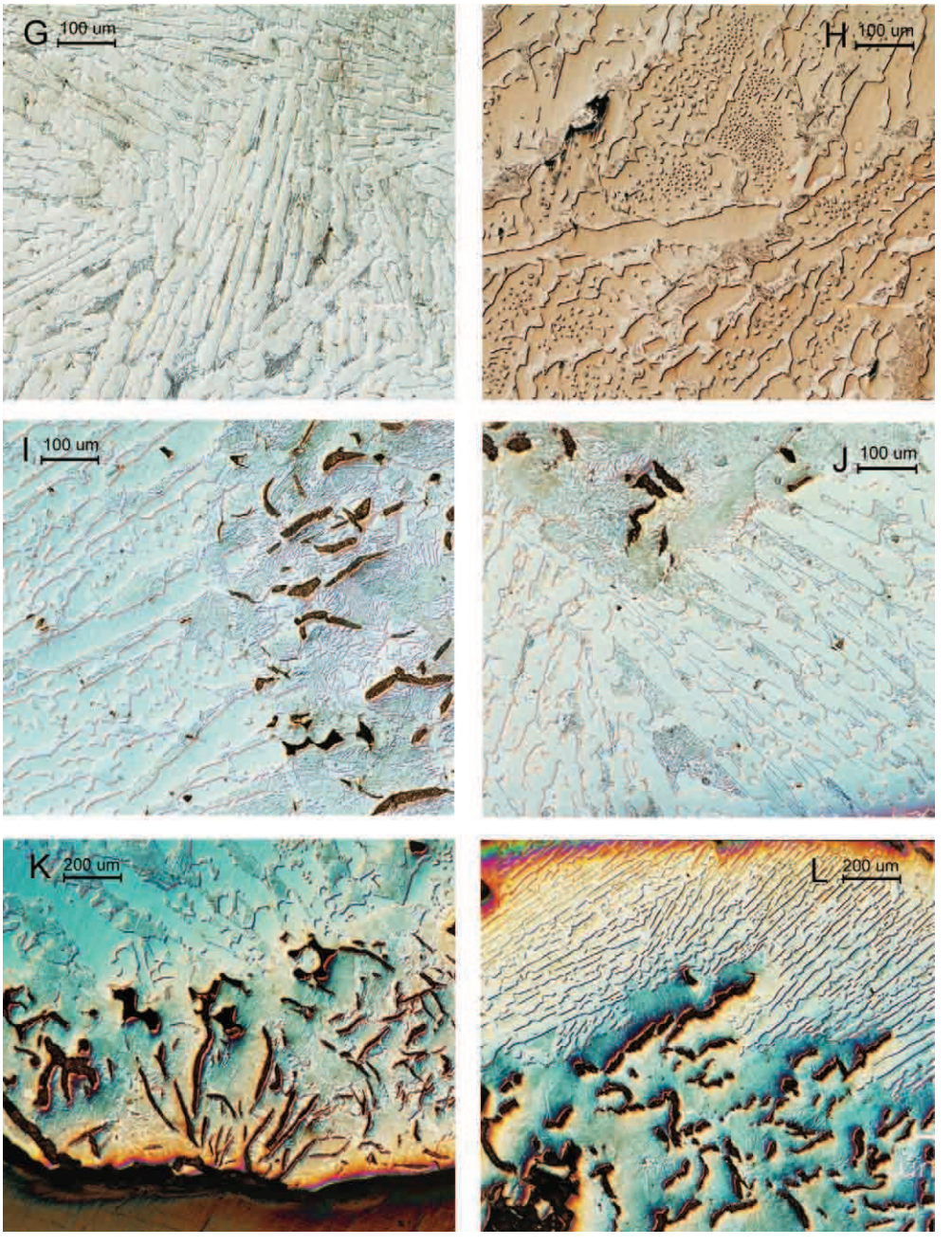

Figure 107: Microphotographs of B3 white cast iron and transitional zones. Photographs by Ph. Fluzin.

Plate XXXI

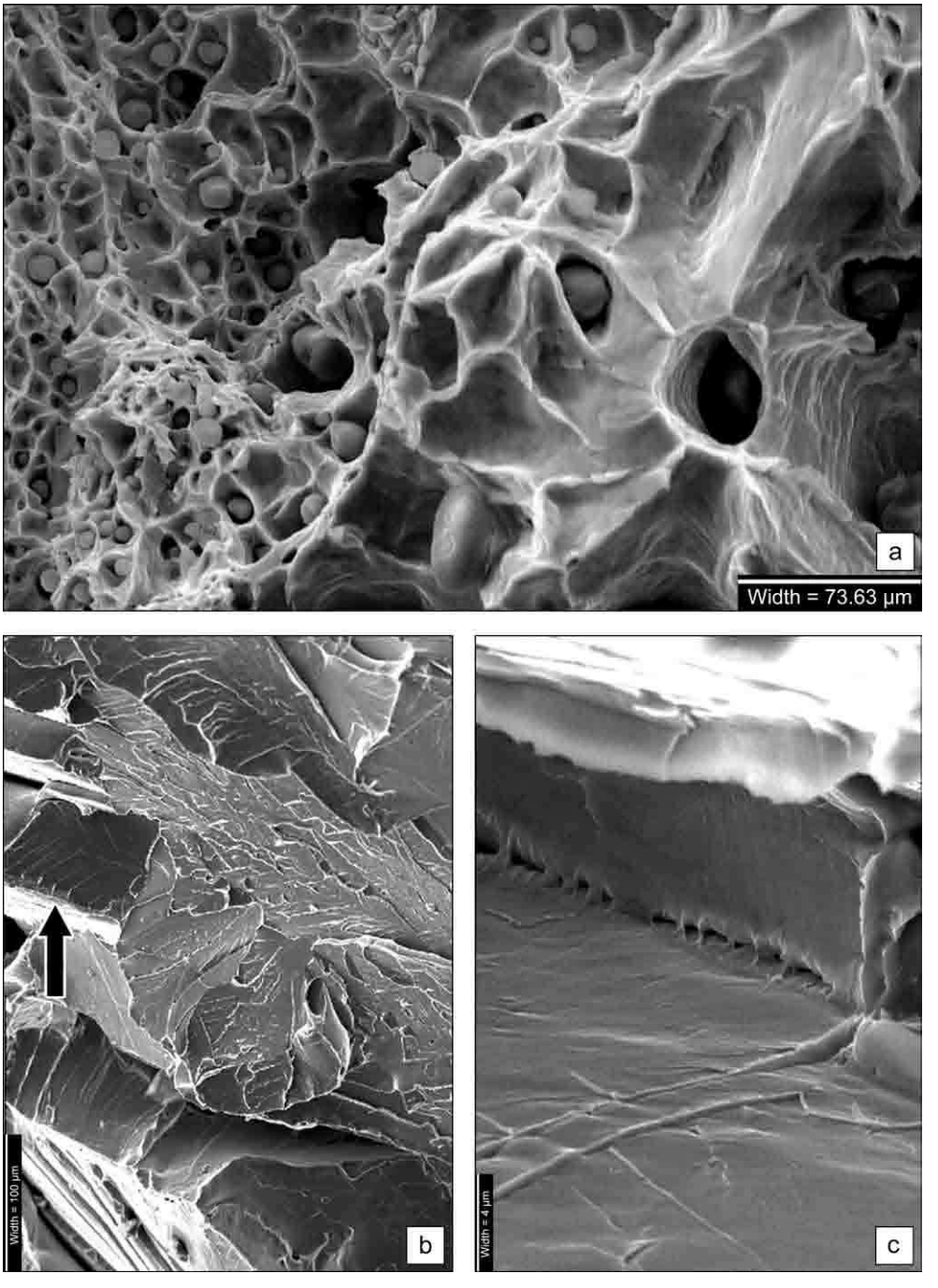

Figure 110: SEM micrograph (a) brittle fractured surface, weld on left, TWI on right. Note the globular slag, (b) cleavage fracture in PWI (magnification bar 100μm), (c) enlargement of crack initiating (magnification bar 4μm).

Plate XXXII

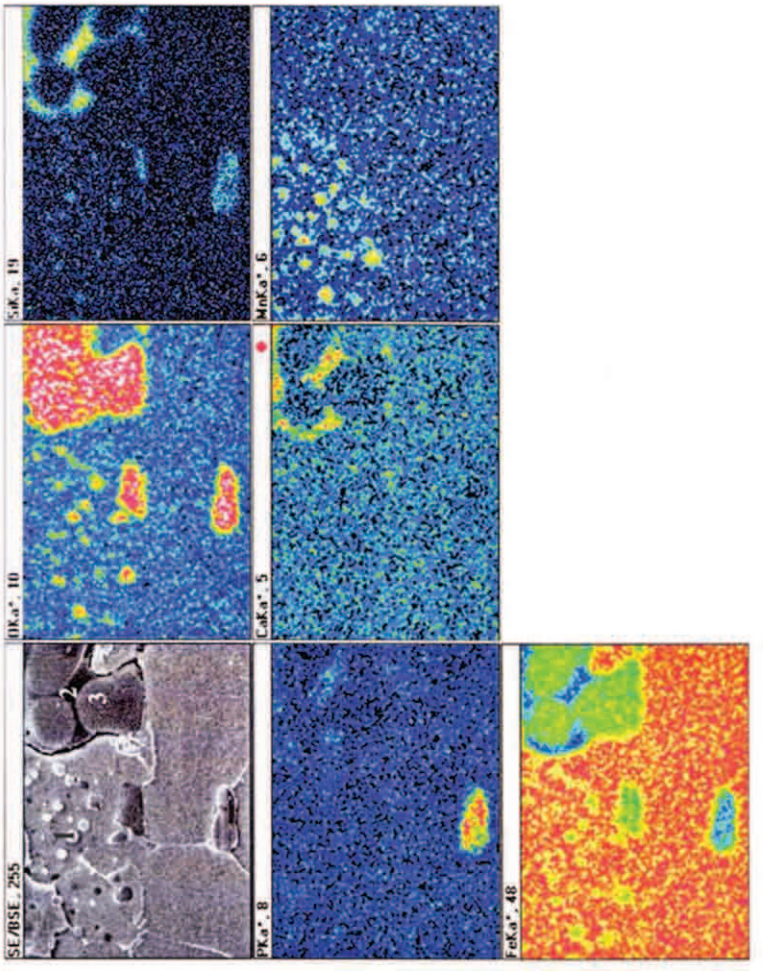

Figure 112: Elemental distribution map for oxygen, silicon, phosphorus, calcium, manganese, and iron with the secondary electron image. Analysis (EDXA-SEM), weight-% as oxide.